Advancements in Empirical Magnetic Field Modeling during the THEMIS and Van Allen Probes era

2015 Space Weather Workshop

April 16th

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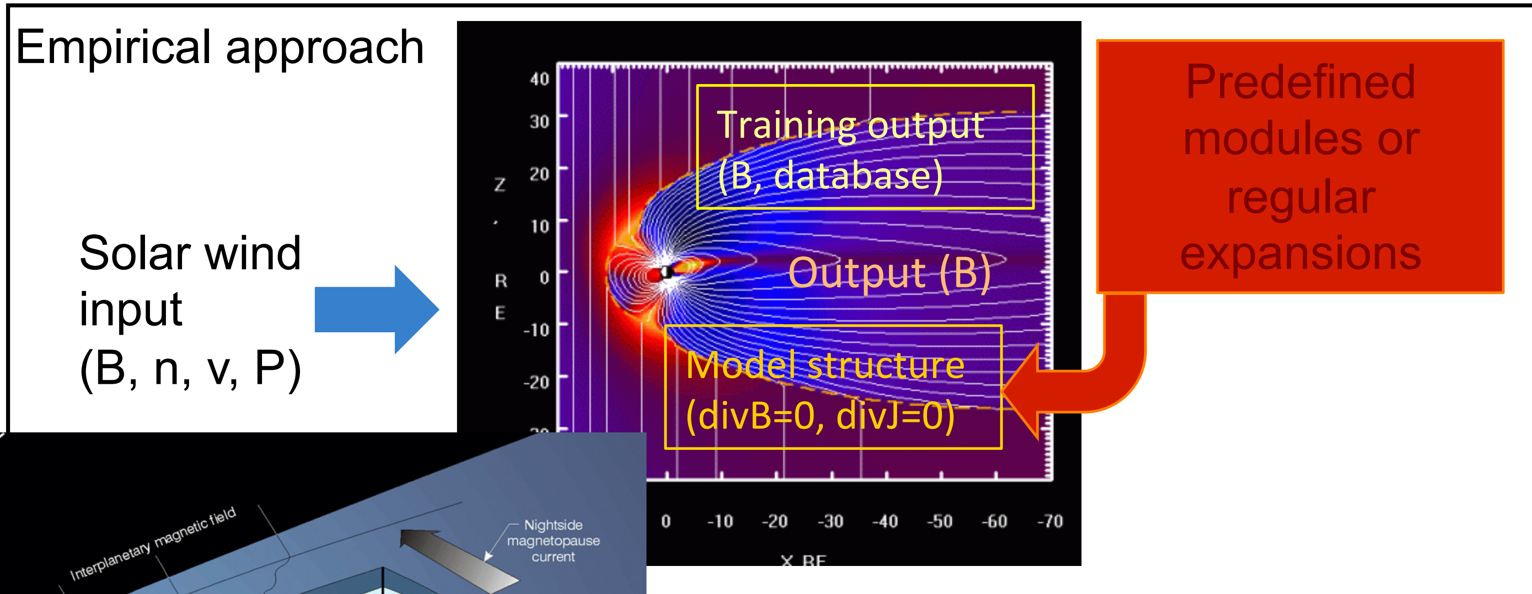
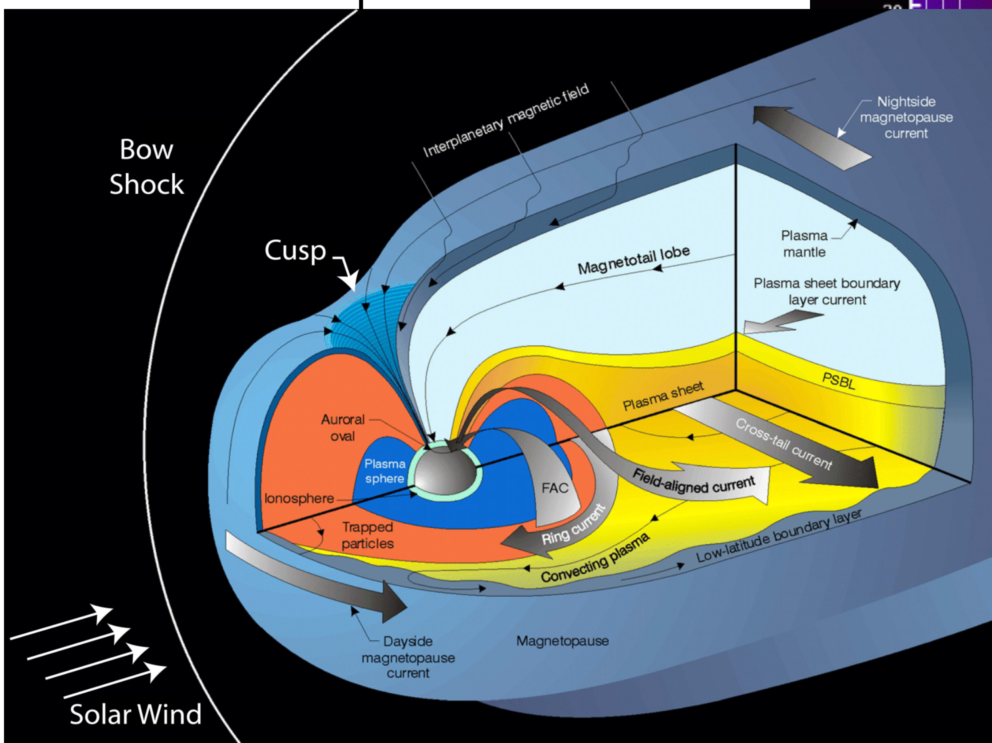
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Overview

- Description of classic Tsyganenko models
- Description of new generation empirical magnetic field models TS07D
- Advancement of TS07D using THEMIS and Van Allen Probes magnetometer data to model the inner-magnetosphere
  - Enhanced equatorial spatial resolution model
  - New Field Aligned Current description

Empirical Approach to modeling the Geomagnetic field



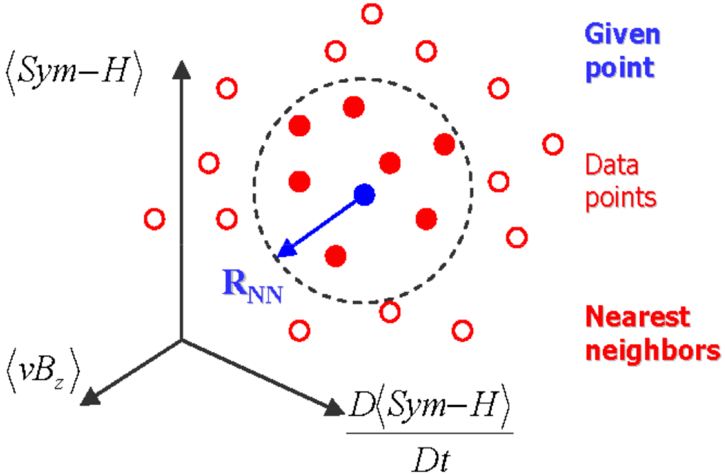


$$\mathbf{B}_E = \mathbf{B}_{CF} + \mathbf{B}_T + \mathbf{B}_{SRC} + \mathbf{B}_{PRC} + \mathbf{B}_{FAC}$$

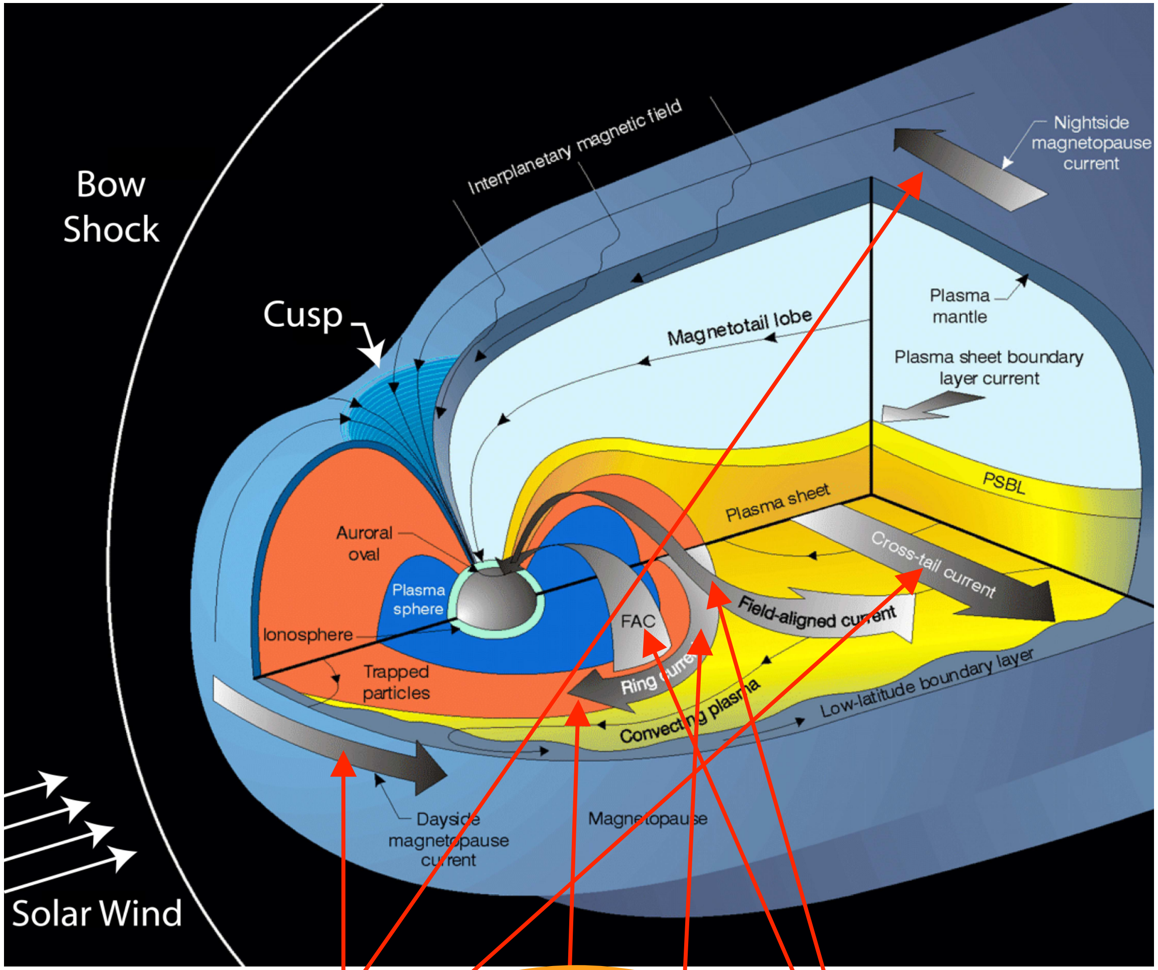
- **Physics is replaced by analytical representations (modules) of current systems using a priori assumptions that are then fit to magnetometer data**

TS07D model: the New Generation of Empirical Magnetic Field Modeling

- 2 Primary Advancements:
- Tail current, symmetric and partial ring currents are replaced by a basis function expansion
- Predefined functional temporal dependence is replaced by dynamical approach using Nearest Neighbors



Sitnov et al., 2008

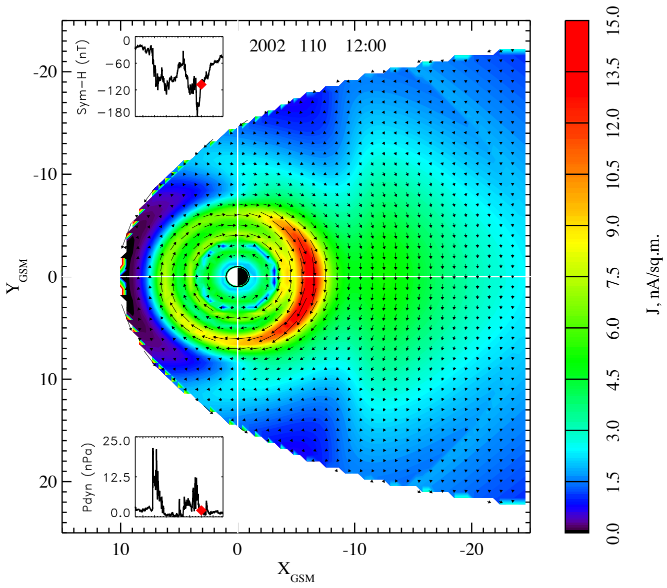


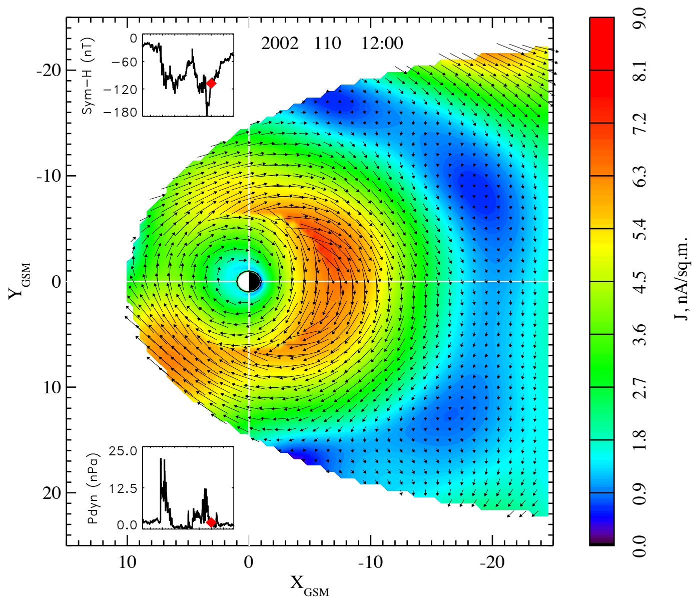
$$\mathbf{B}_E = \mathbf{B}_{CF} + \mathbf{B}_T + \mathbf{B}_{SRC} + \mathbf{B}_{PRC} + \mathbf{B}_{FAC} + \cancel{\mathbf{B}_{INT}}$$

$$\mathbf{B}_{EQ}$$

Classic vs. New Generation of Models

TS05 vs. TS07D





- **TS07D is free of restrictions intrinsic to earlier models**
  - **This allows for realistic topology and temporal evolution of storm-time equatorial currents**
  - **Spatial resolution of equatorial currents are bounded by available magnetometer data**
- **This makes it agreeable for scientific studies**
  - **Such as to study storms with different solar wind drivers: CMEs [*Sitnov et al*. 2008] and CIRs [*Sitnov et al*. 2010]**
  - **And different convection modes such as SMC *[Stephens et al.* 2013]**

TS07D: Equatorial Magnetic Field Description

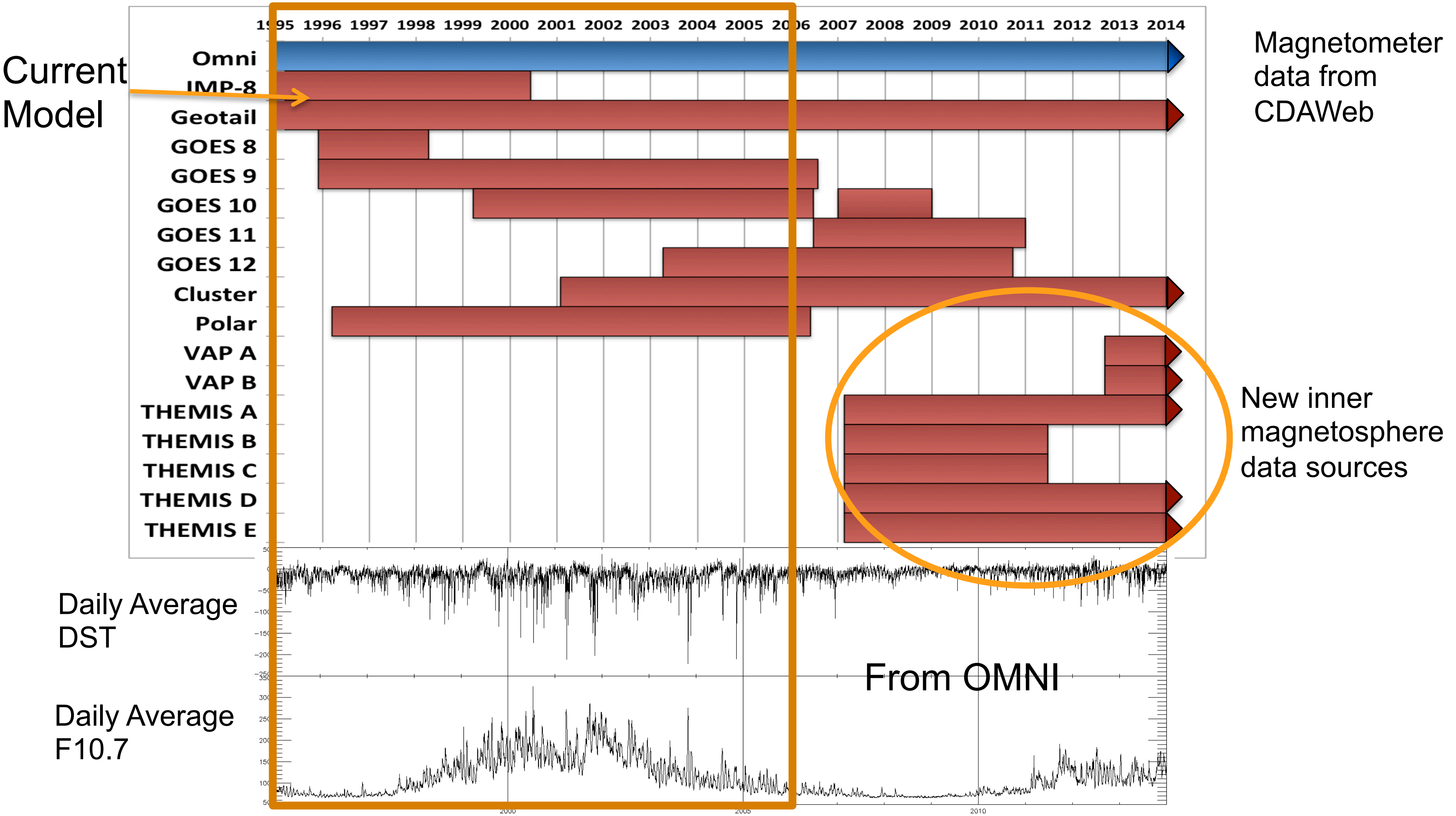
$$\mathbf{B}_{Eq}\left(\mathrm{P_d}\right) = \sum_{n=1}^{N} t_n^{(s)} \mathbf{B}_{Tn}^{(s)} + \sum_{m=1}^{M}\sum_{n=1}^{N} t_{mn}^{(o)} \mathbf{B}_{Tmn}^{(o)} + \sum_{m=1}^{M}\sum_{n=1}^{N} t_{mn}^{(e)} \mathbf{B}_{Tmn}^{(e)}$$

- **Basis Function Expansion representation of equatorial field gives arbitrary spatial resolution**
- **Bounded only by ability to fit magnetometer data to expansion**

$$coeffs = 2\left(N + 2\left(N \cdot M\right)\right)$$

  - **TS07D uses N = 5, M = 4, for 90 equatorial coefficients (current model)**
  - **This is too coarse to describe the inner magnetosphere**
  - **For N = 20, M = 6, we now have 520 coefficients!**
  - **We need more magnetometer data to constrain the model**

Expanding the magnetometer database

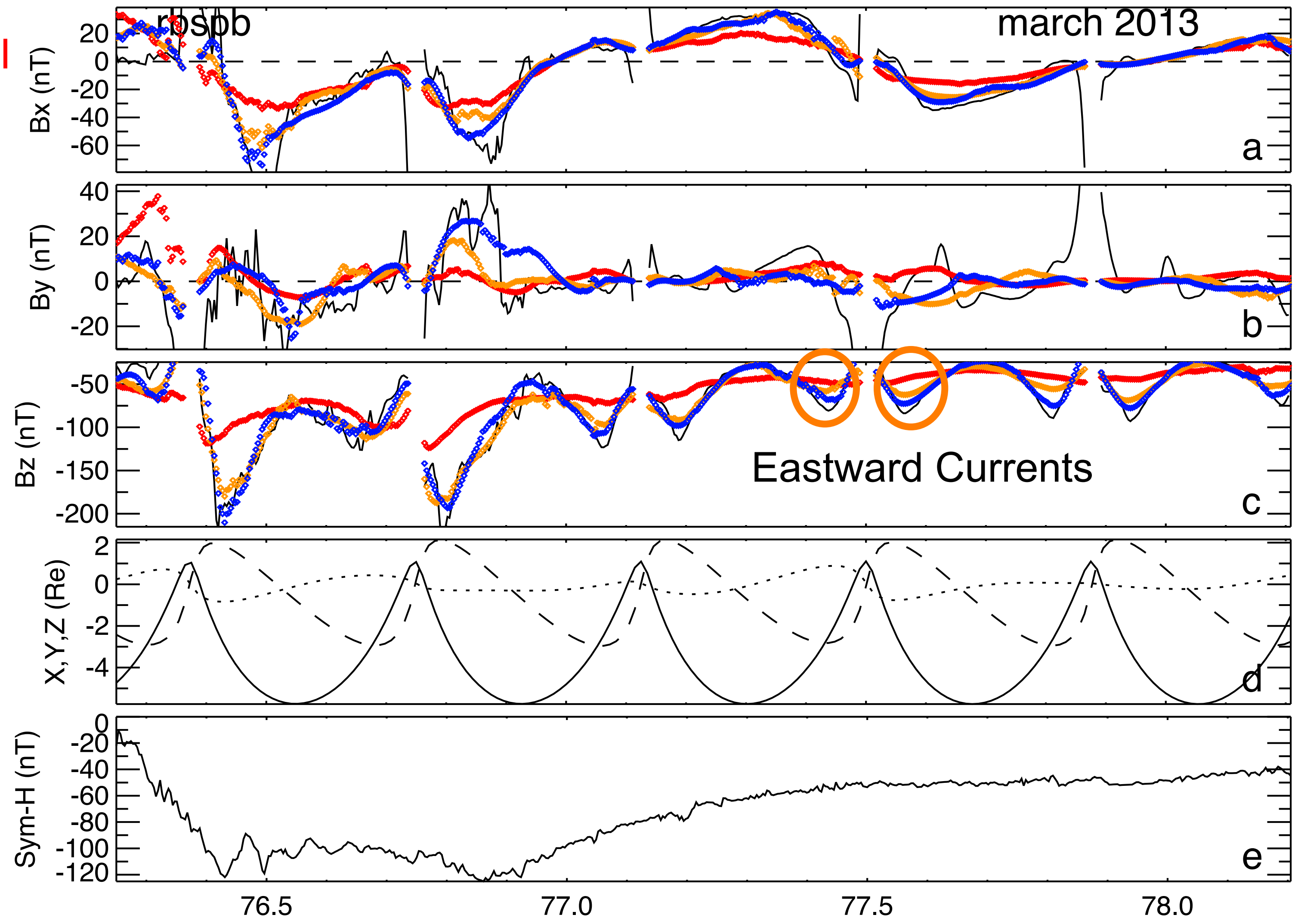


Utilizing Van Allen Probes to reconstruct the inner magnetosphere

TS07D Model M=4, N=5

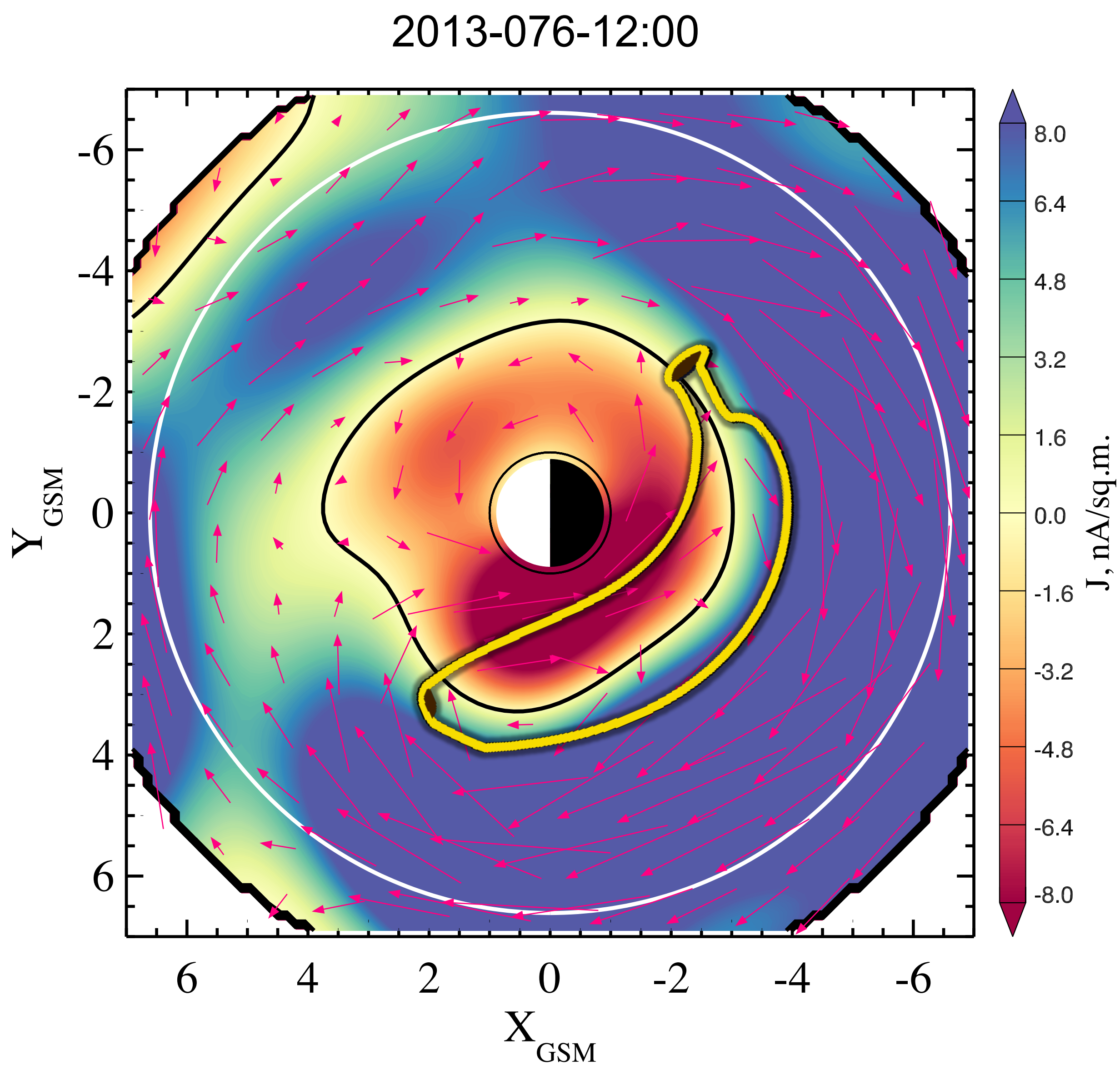
Model fit to VAP-B with M=6, N=8

Model fit to VAP-B with M=6, N=20

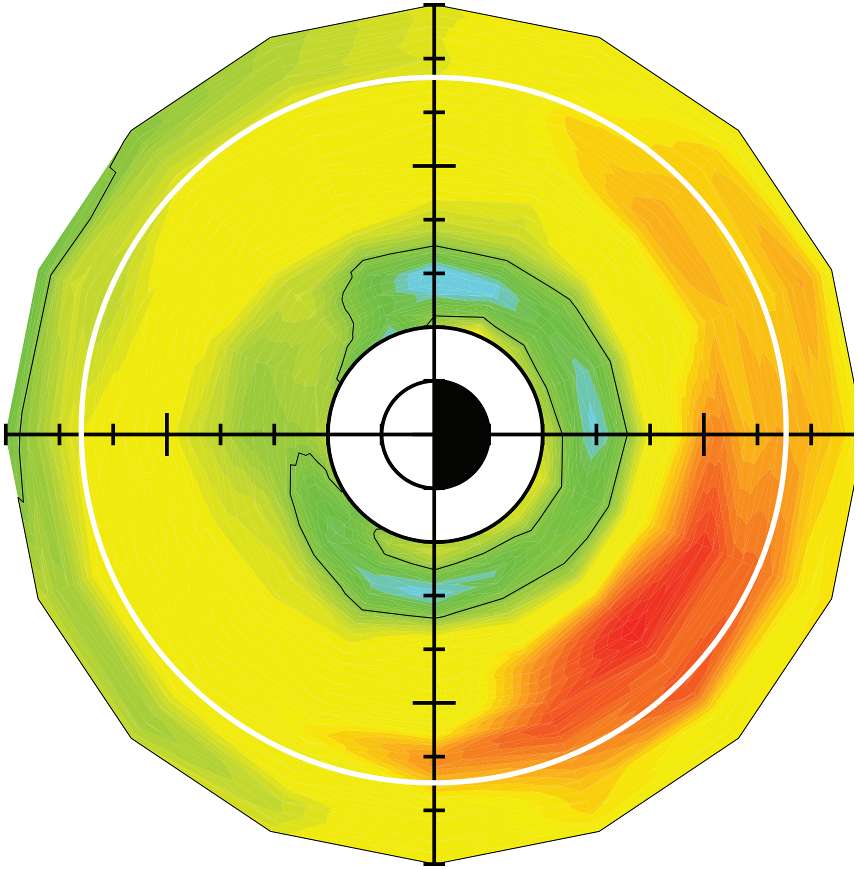


Reconstruction of recovery phase of March 2013 storm

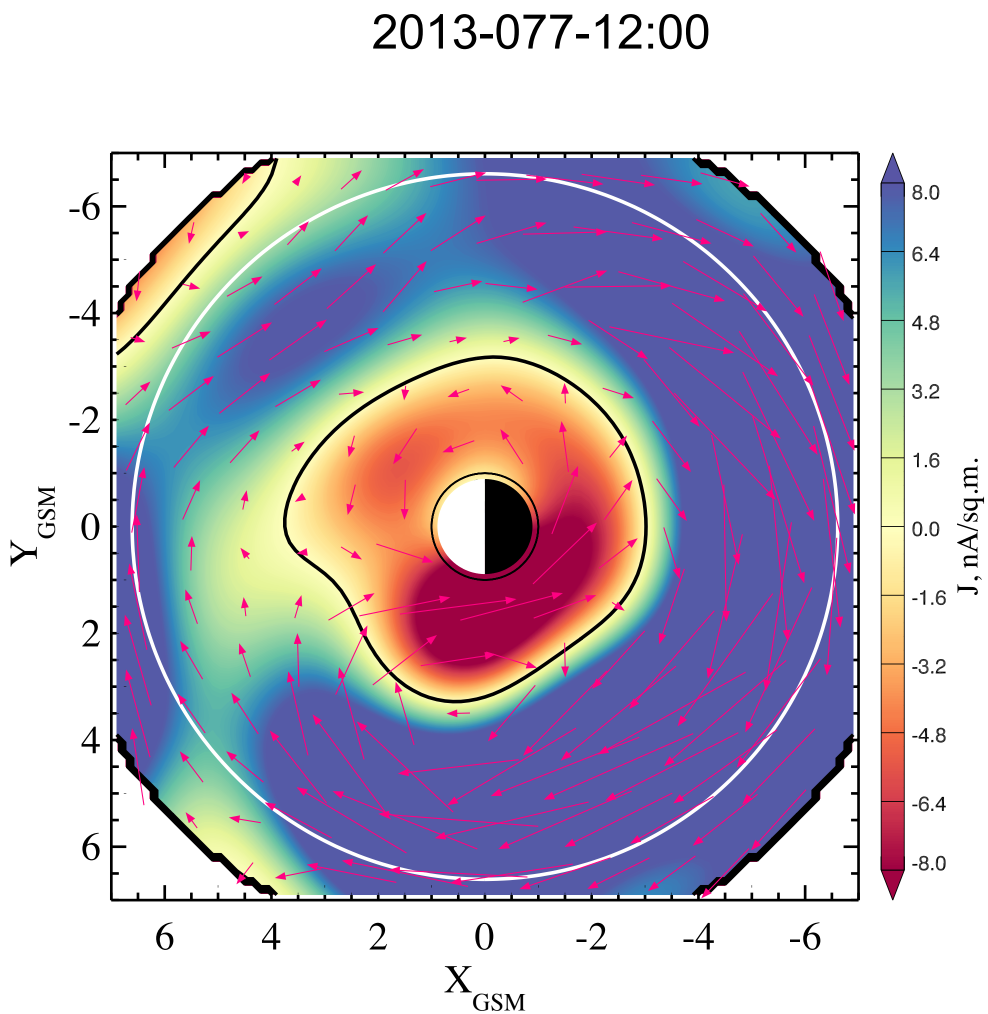
- **Sample database using TS07D database +Van Allen Probes and THEMIS**
- **N=20, M=6**
- **Model clearly resolves both the Westward and Eastward ring currents**
- **Also resolves the 'Banana current' postulated by *Roelof* 1989 and *Liemohn et al.*, 2013**



Comparison with other Empirical Studies



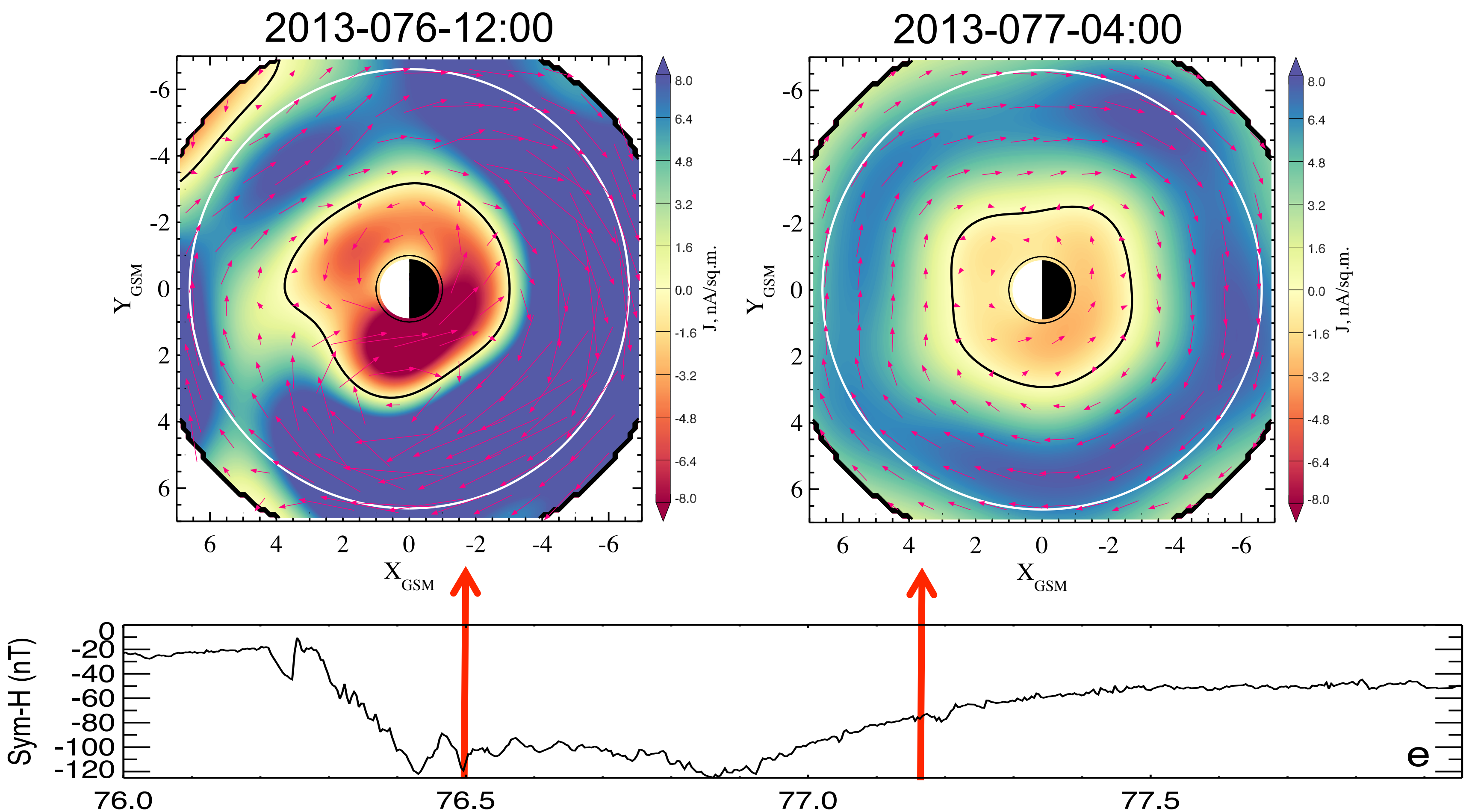
Equatorial ring current distribution for -60 nT > Dst* > -80 nT [Le et al., 2004]



Evolution of Eastward Currents

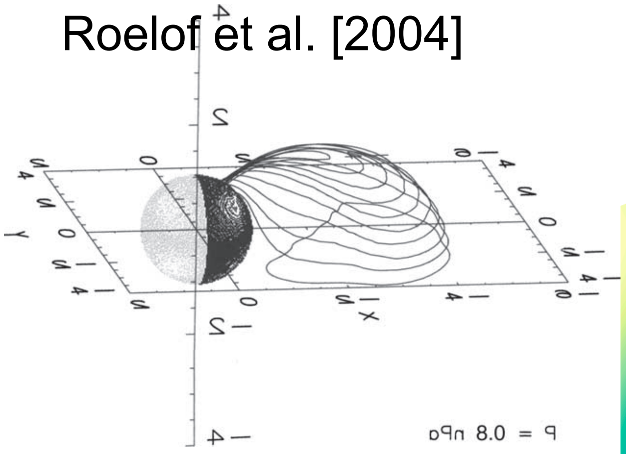
During SymH* min., asymmetries lead 'Banana' currents to dominate over symmetric eastward currents

In the recovery, symmetric eastward currents dominate the banana currents

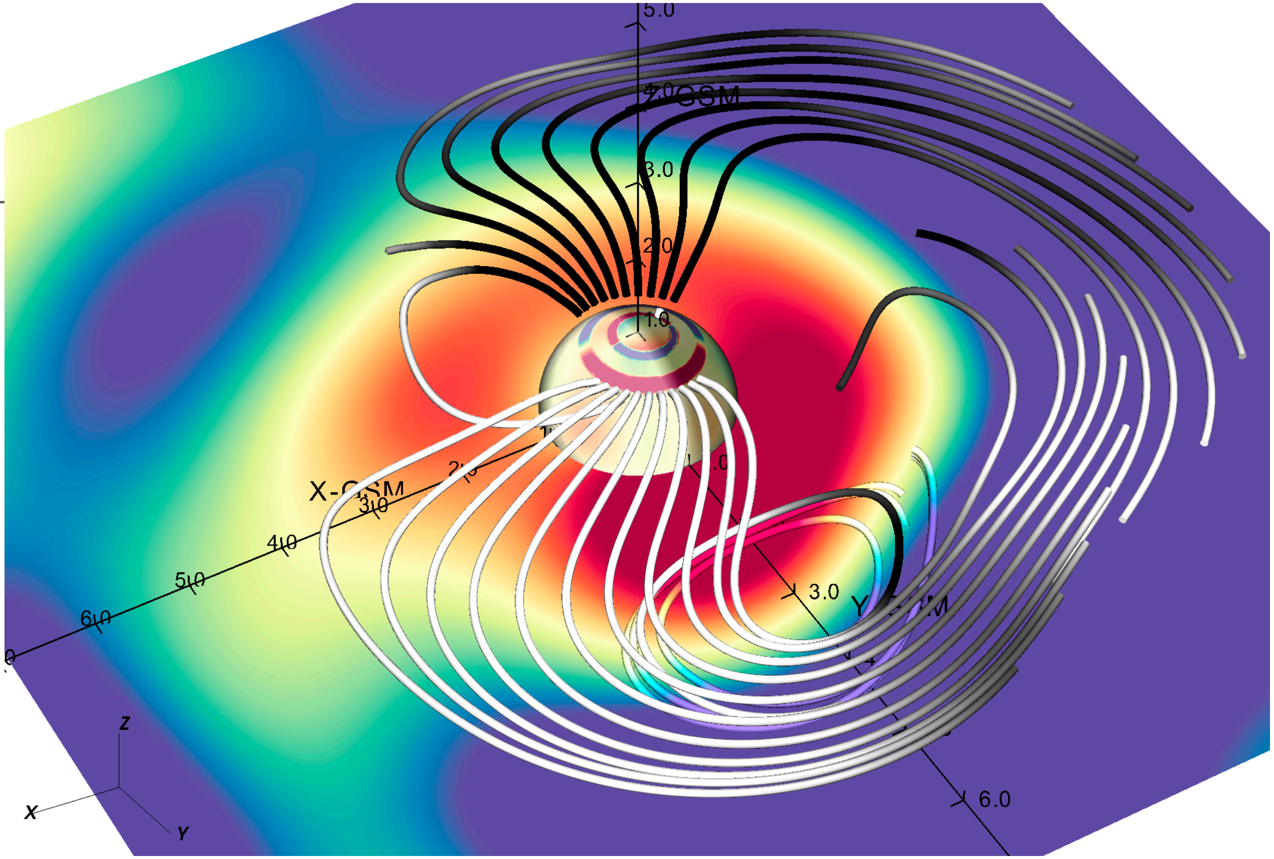


Comparison with ENA images and kinetic models

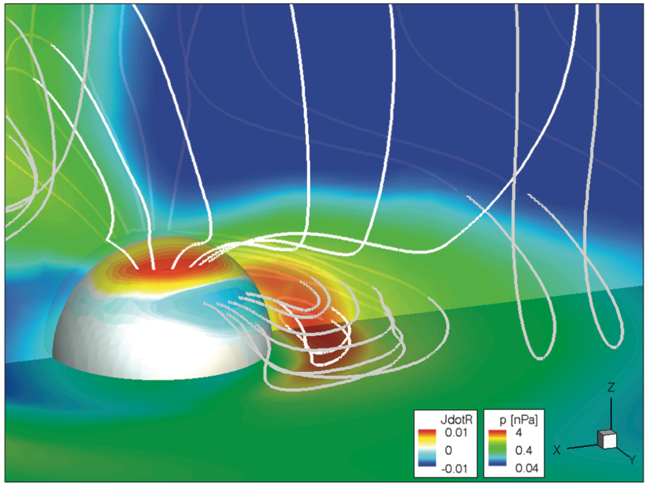
Roelof et al. [2004]



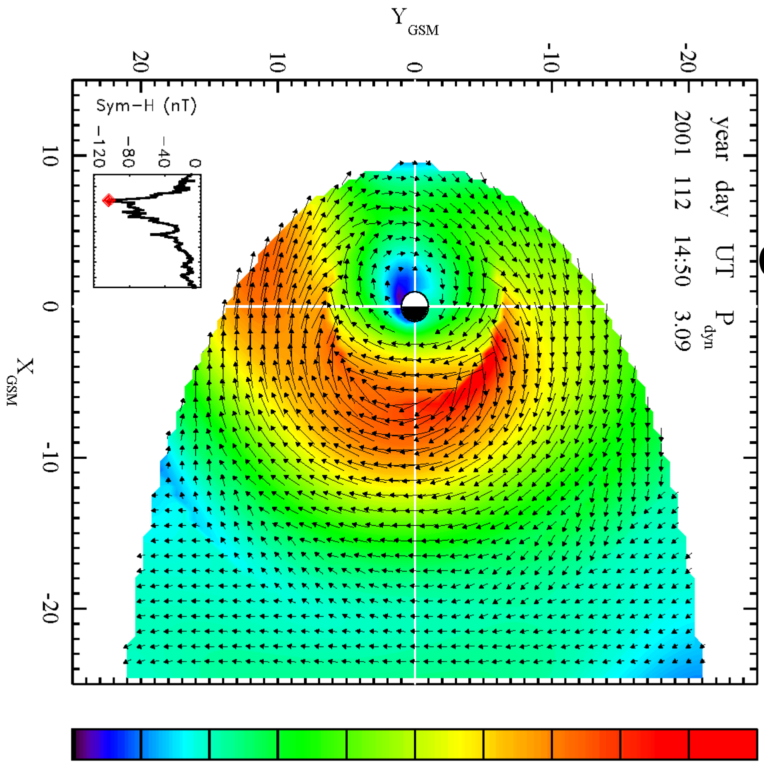
Empirical current picture (2013-076 12:00)

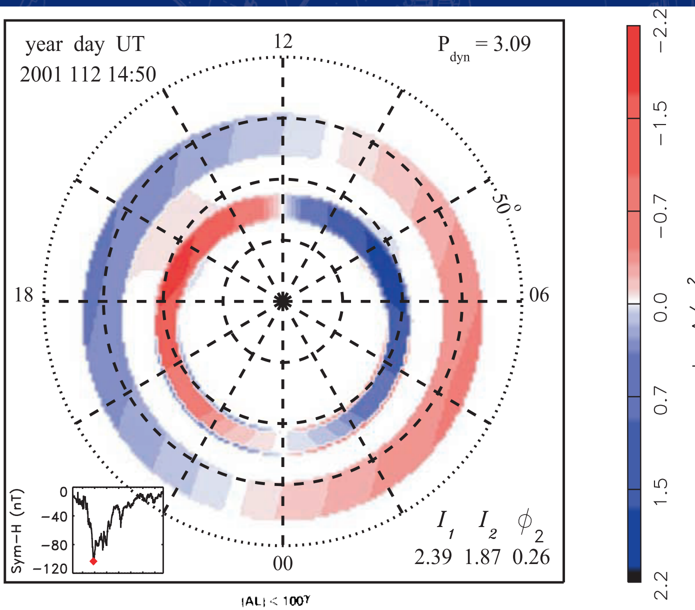


Liemohn et al. [2013]

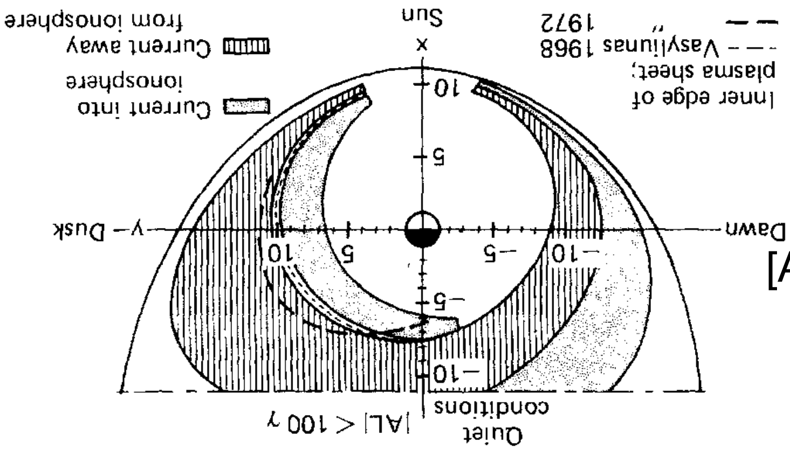


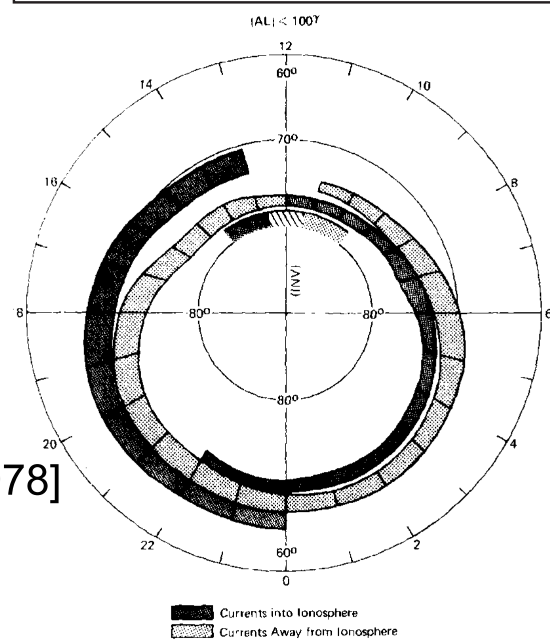
Advancements in Field Aligned currents





Current TS07D model



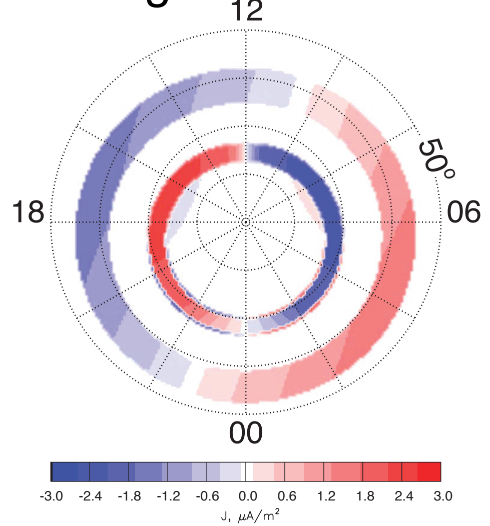


Potemra

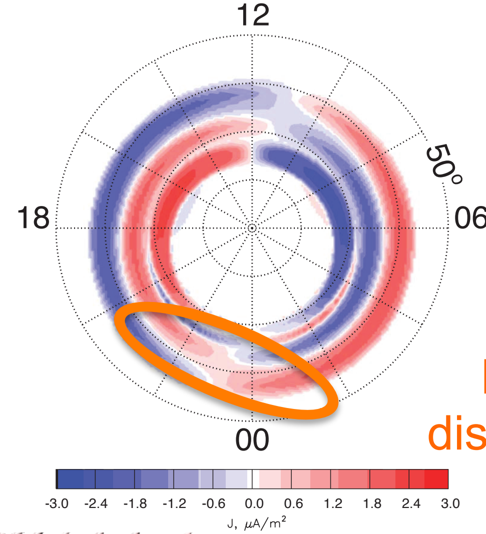
[ASS, 58, 207,1978]

Advancements in Field Aligned currents

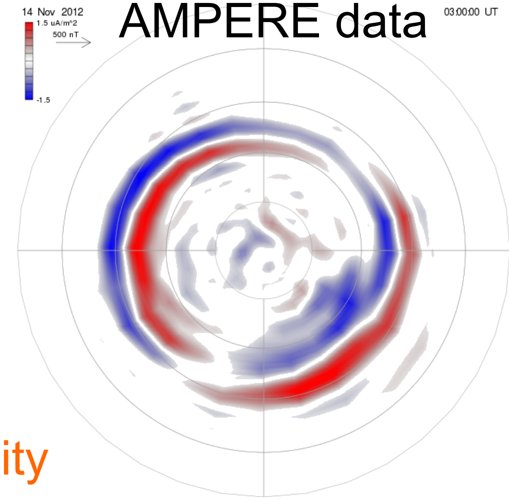
Original TS07D



TS07D w/ advanced FAC



AMPERE data

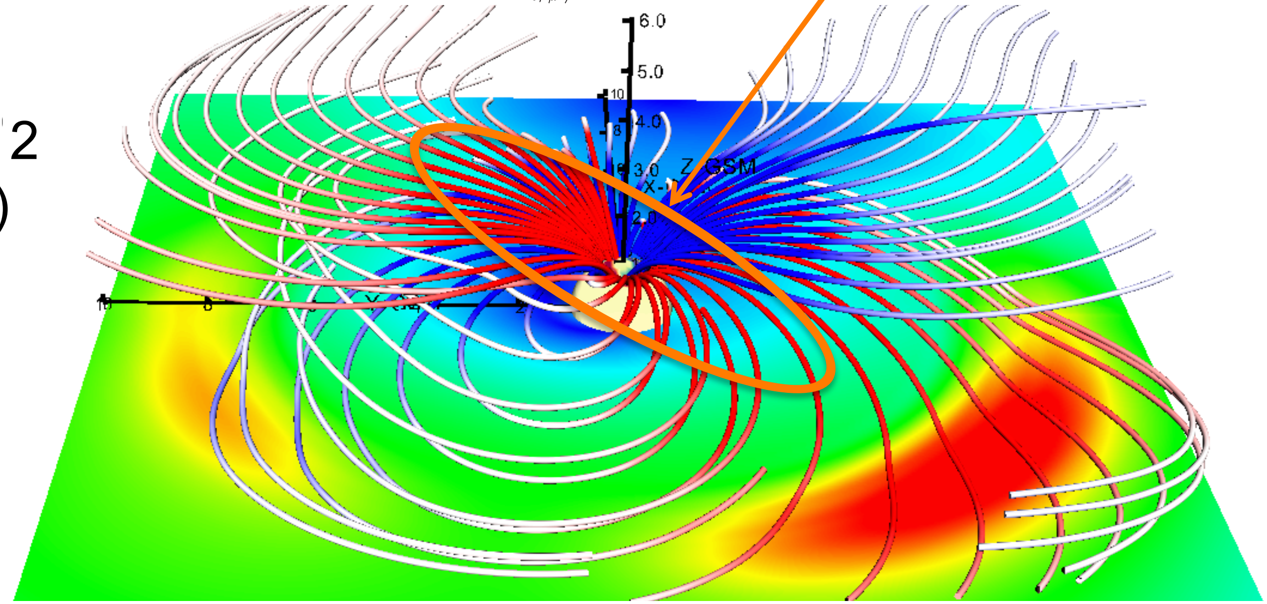


Harang discontinuity

14 November 2012 storm (319-03:00)

319 03:00

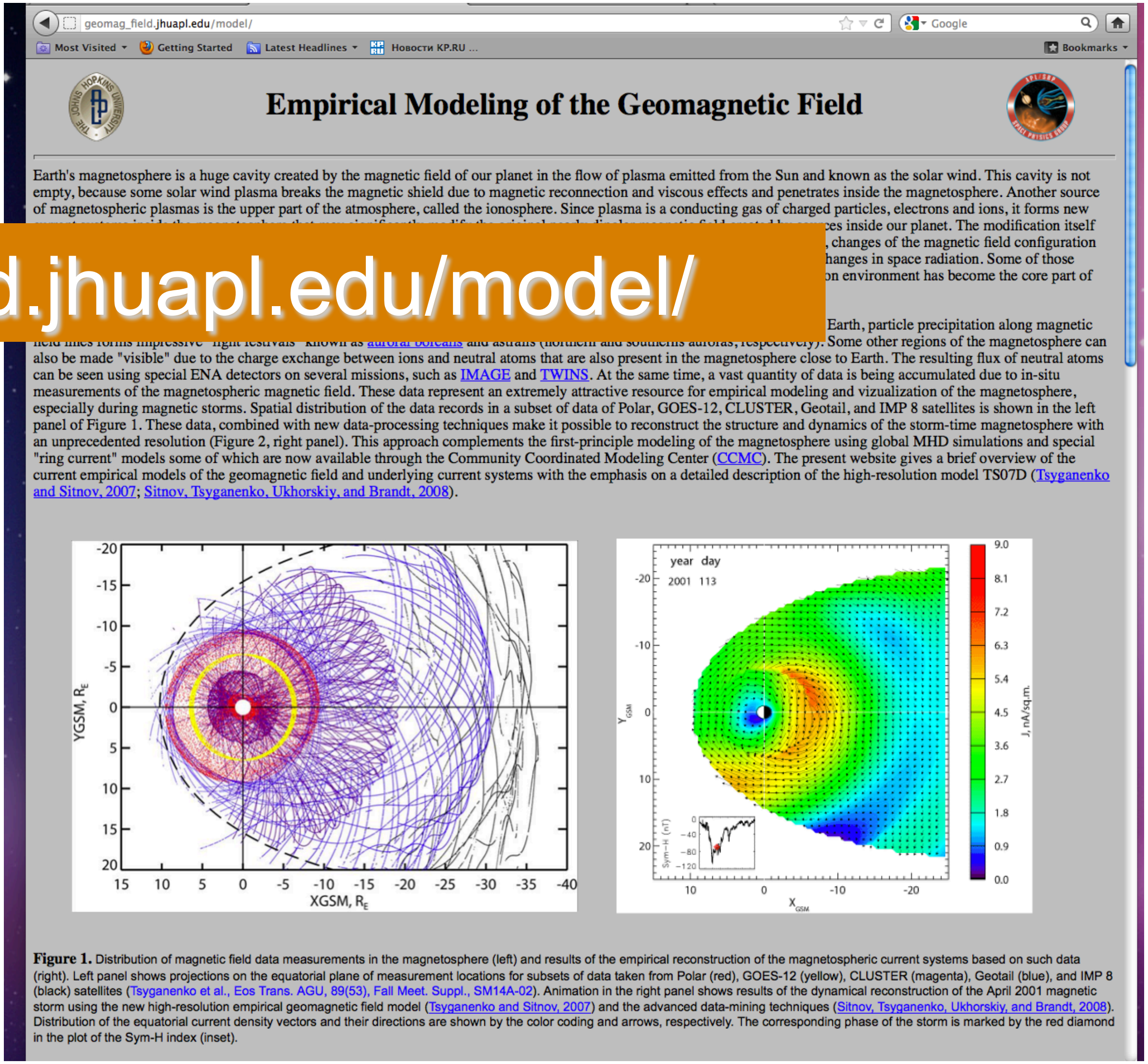
P_{dyn}=1.78



Using TS07D

Model website

http://geomag_field.jhuapl.edu/model/



Using TS07D

Source Code

```
c@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

      P r o g r a m   TS07D

c-------------------------------------------------------------------------
c
      REAL*8 A,PDYN,TSS,TSO,TSE

      CHARACTER*80 NAMETSS(5),NAMETSO(5,4),NAMETSE(5,4)

      PARAMETER (NTOT=101)

      COMMON /GEOPACK1/ AAA(10),SPS,CPS,BBB(
      COMMON /PARAM/ A(NTOT)
      COMMON /INPUT/  PDYN

      COMMON /TSS/ TSS(80,5)
      COMMON /TSO/ TSO(80,5,4)
      COMMON /TSE/ TSE(80,5,4)

      DIMENSION PARMOD(10)
      DIMENSION CXY(101,101),CJY(101,101),XX(101),ZZ(101)

      DATA NAMETSS/                              !  SHIELDING FIELD PARAMETERS:
     *'C:\Work\TSG_DYN_PAR\tailamebhr1.par',     !   MAKE SURE TO MODIFY THE PATH TO THE ACTUAL
     *'C:\Work\TSG_DYN_PAR\tailamebhr2.par',     !   STORAGE FOLDER, IF NECESSARY
     *'C:\Work\TSG_DYN_PAR\tailamebhr3.par',
     *'C:\Work\TSG_DYN_PAR\tailamebhr4.par',
     *'C:\Work\TSG_DYN_PAR\tailamebhr5.par'/
      DATA NAMETSO/
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_11.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_21.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_31.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_41.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_51.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_12.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_22.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_32.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_42.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_52.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_13.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_23.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_33.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_43.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_53.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_14.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_24.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_34.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_44.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_o_54.par'/
      DATA NAMETSE/
     *'C:\Work\TSG_DYN_PAR\tailamhr_e_11.par',
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     *'C:\Work\TSG_DYN_PAR\tailamhr_e_14.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_e_24.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_e_34.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_e_44.par',
     *'C:\Work\TSG_DYN_PAR\tailamhr_e_54.par'/
c
      DO 1001 IREAD=1,5
      OPEN (UNIT=1,FILE=NAMETSS(IREAD))
      READ (1,200) (TSS(KK,IREAD),KK=1,80)
 200  FORMAT(G17.10)
 1001 CLOSE(1)

      DO 1002 IREAD=1,5
        DO 1003 KREAD=1,4
      OPEN (UNIT=1,FILE=NAMETSO(IREAD,KREAD))
```

http://geomag_field.jhuapl.edu/model/

Model website

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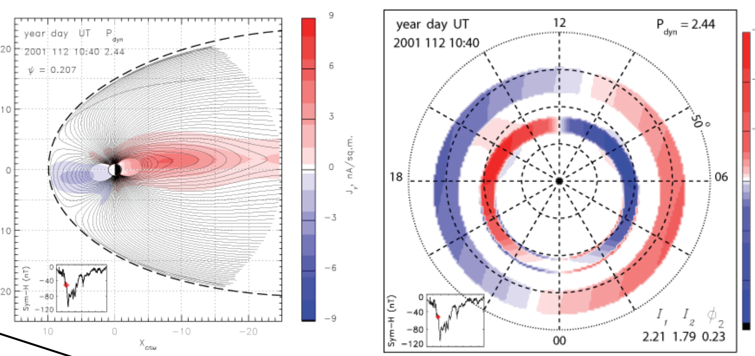

Figure 3. Magnetic field lines, the color-coded dawn-dusk component of the current density (left) and the distribution of Birkeland currents at the ionospheric level in the main phase of the April 2001 magnetic storm (Sitnov, Tsyganen[illegible]rskiy, and Brandt, 2008).

The source code of the TS07D model can be f[illegible]und **HERE**. Its i[illegible]erface is similar in structure to previous model[illegible] as TS05 (see cla[illegible]ical empirical geomagnetic field models). However, the use o[illegible] the code has t[illegible]o important distinctions. **First**, it requires a s[illegible] of **AUXILIARY FILES** 'tail[illegible] that contain the amplitudes of the shielding coefficients [illegible] basis functions of the equatorial current system (pre[illegible]ntly their number is 45). **S[illegible]ond**, the input of the code requires, along with the **GSM coordinates** of the point, where the magnetic field is calculated, and the **time**, [illegible] value of the **dynamical pressure** PDYN and the set of dynamical **code coefficients**, which is found using the data mining (NN) procedure and a fitting code, and which is unique for the given moment in time (note, that the time value is also used to calculate the **tilt angle**). At present, the state parameters are provided in the following **LIST OF PROCESSED STORMS** with 1 hour interval (the highest temporal resolution of the present model is 5 min). The performance of the code is not limited to storms, although the NN search involves a few-hour averaging in time and thus reflects largely storm time scales. We plan to populate the list of available events as a part of the specific research projects. The **RUN ON REQUEST** tool, combining the aforementioned data mining and fitting procedures and covering the period 1995-2005 (in-sample modeling regime, corresponding to the extension of the present model database), is now available.

As is seen from the above, TS07D is complementary both to the available first-principle models and to the existing empirical geomagnetic field models. The price for high resolution in space and high flexibility in time variations is quite high for the present model. The need to re-calculate the model coefficients at every new moment in time makes it similar in performance to the present first-principle MHD and the ring current models. Note, that although the latter models are presently limited in the global description of the magnetosphere, potentially they should provide the most comprehensive information on its structure and dynamics, including both the magnetic field and other key parameters, such as the electric field and plasma moments. At the same time, the information on the global structure of the magnetic field and global current distribution provided by the present model may help in benchmarking and coupling of the aforementioned first-principle models as well as in the data assimilation.

Necessary Static Data Files

Using TS07D

- Model link is on Van Allen Probes Science Gateway
- http://rbspgway.jhuapl.edu/

Home

Van Allen Probes

SCIENCE GATEWAY

MISSION HOME | GATEWAY HOME | SPACE WEATHER | DATA | INSTRUMENTS | ANALYSIS | PLANNING | GENERAL

Enter Username | Login | Create Account

ANALYSIS

- Models
- Team Area

Home

ANALYSIS: Relevant Models of Interest

CCMC	The CCMC hosts a variety of models covering the entire domain from the solar corona to the Earth's upper atmosphere. CCMC works with model developers to make their models available to a wide research community through runs on request as well as instant runs.
DREAM	The Dynamic Radiation Environment Assimilation Model (DREAM) is a Space Weather model developed at Los Alamos National Laboratory to understand and to predict hazards from the natural space environment and artificial radiation belts produced by high altitude nuclear explosions (HANE) such as Starfish.
AE-8/AP-8	CCMC Services available for AE-8/AP-8 RADBELT. A software package that includes (1) an improved and updated version of the old MODEL program (MODEL87), (2) an interactive driver program (RADBELT), (3) the electron AE-8 and proton AP-8 flux maps for solar maximum and minimum, and (4) the interpolation subroutines. RADBELT and MODEL87 compute omnidirectional, integral, or differential (in energy) fluxes of electrons and protons trapped in Earth's radiation for specified energy, L-value, and B/Bo range (B/Bo is magnetic field strength normalized to the equatorial value). The fluxes are obtained by an interpolation procedure from the AE-8 and AP-8 trapped particle flux maps. The RADBELT program allows the user to specify input parameters and options online and generates flux tables that can be stored for later use.
SIZM	Inner Zone Model. A radiation belt proton, antiproton, and secondary model.
Tsyganenko Geomagnetic Field Model and GEOPACK libraries	The Tsyganenko models are semi-empirical best-fit representations for the magnetic field, based on a large number of satellite observations. The models include the contributions from major external magnetospheric sources: ring current, magnetotail current system, magnetopause currents, and large-scale system of field-aligned currents. The Tsyganenko model suite also includes GEOPACK library with 20 FORTRAN subroutines. Provides instantaneous calculation of external and internal geomagnetic fields along a field line and at a specified point based on T96 and Geopack08.
Empirical Geomagnetic Field Models	Tsyganenko and Sitnov empirical models of geomagnetic field. Recent models (e.g. TS07D) provided a relativistic high-resolution description of the magnetic field evolution in the inner magnetosphere during geomagnetic storms as a function of the solar wind and geomagnetic input parameters. Model applications include the magnetic mapping and correlation of spacecraft observations, computation of the adiabatic invariants of particle motion in the belts, the analysis of particle transport and losses from the belts, global visualization of storm-time magnetospheric-ionospheric current systems including computations of the inductive electric field induced by their storm-time reconfigurations. Web resources include the descriptions of the models and model parameters as well as Run-On-Request Tools. Given the increased spatial resolution of TS07D, custom fits are needed for each time interval. These are ascii files that represent the fit coefficients in the model, and must be loaded to evaluate it. Hourly epochs have been fit, while higher resolutions are interpolations of the hourly files. The files are can be downloaded here.
Empirical Models of Ionospheric Electrostatic Potential	Empirical models of ionospheric electrostatic potential combined with geomagnetic field models provide global maps of the electrostatic field across the inner magnetosphere for the analysis of storm-time convection and the buildup of the ring current and the radiation belt seed population.
AF-GEOSPACE	A user-friendly graphics-intensive software program bringing together many of the space environment models, applications and visualization products developed by the Air Force Research Laboratory and others in the space weather community.

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Run-on-Request Webpage

Location: http://sd-www.jhuapl.edu/geostorm/magModel.pl

Mag Model Coefficients!

Get Data

Enter a UTC Time Range

Time Range	
Start Date:	Day of year (1-366): 082 Year (1995-2005): 2002 Hour (0-23): 10
Stop Date:	Day of year (1-366): 085 Year (1995-2005): 2002 Hour (0-23): 10

Enter Options

Options	
Number of Fitting Iterations (1-99):	20
Recalculate Simplex Parameters:	yes no
Initial Coefficient File:	Use Default Use: Choose File No file

Get Data

Mag Model Coefficients!

If you close this browser window, it is vital that you **remember your unique url** so that you may retrieve your data. Depending on the precise parameters for your fit, thefitting process can take from several minutes to several hours. Refreshing your pagewill give you an updated status.

Clicking the links will take you to anther page where you can retrieve your data.

Status
Nearest Neighbor Time
Nearest Neighbor Spacecraft
Fitting 4 of 72

Key
not started
in progress
completed
failed

Mag Model Coefficients!

Coefficients Listing	
File:	bfsf_001.par
File:	bfsf_002.par
File:	bfsf_003.par
File:	bfsf_004.par
File:	bfsf_005.par
File:	bfsf_006.par
File:	bfsf_007.par
File:	bfsf_008.par
File:	bfsf_009.par
File:	bfsf_010.par
File:	bfsf_011.par

Conclusions

- Current magnetic field models are inadequate in reconstructing the inner magnetosphere and field aligned currents
- The Basis Function expansion approach along with the Nearest-Neighbors binning method and plenty of magnetometer data make it possible to reconstruct the inner magnetosphere
- This approach can clearly resolve both the symmetric Eastward currents and the asymmetric Eastward ‘Banana’ currents
- By introducing overlapping FAC modules, the model can reconstruct the realistic ‘spiral’ Birkeland current pattern
- A new higher spatial resolution model would be valuable tool in inner-magnetospheric and space weather studies

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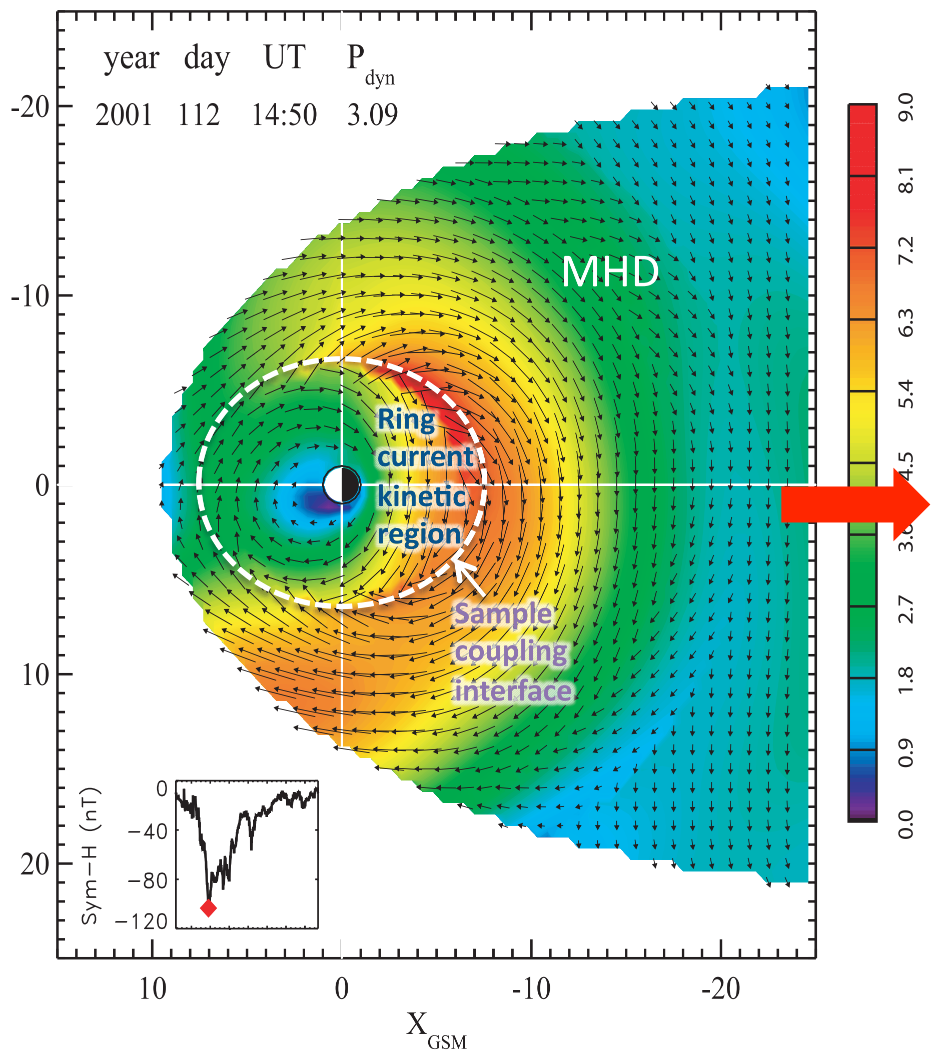
Complementing First-principles models



$$\mathbf{j}\times\mathbf{B} = \nabla p$$

Adjusting storm time scale equation of state

Adjusting external boundary conditions

MHD equations

$$\partial\rho/\partial t + \nabla(\rho\mathbf{v}) = 0$$

$$\partial\mathbf{v}/\partial t + (\mathbf{v}\nabla)\mathbf{v} = \rho^{-1}(\mathbf{j}\times\mathbf{B} - \nabla p)$$

$$(\partial/\partial t + \mathbf{v}\nabla)p = -\gamma p\nabla\mathbf{v}$$

$$\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \eta\mathbf{j}$$

RCM equations

$$(\partial\rho/\partial t + \mathbf{v}_D\nabla)\eta_k = -\eta_k/\tau_k$$

$$\mathbf{j}\times\mathbf{B} = \nabla p$$

$$pV^{5/3} = (2/3)\sum_k \eta_k|\lambda_k|$$

$$j_{\parallel nh} - j_{\parallel sh} = B_i(\mathbf{B}/B^2)(\nabla V\times\nabla p)$$

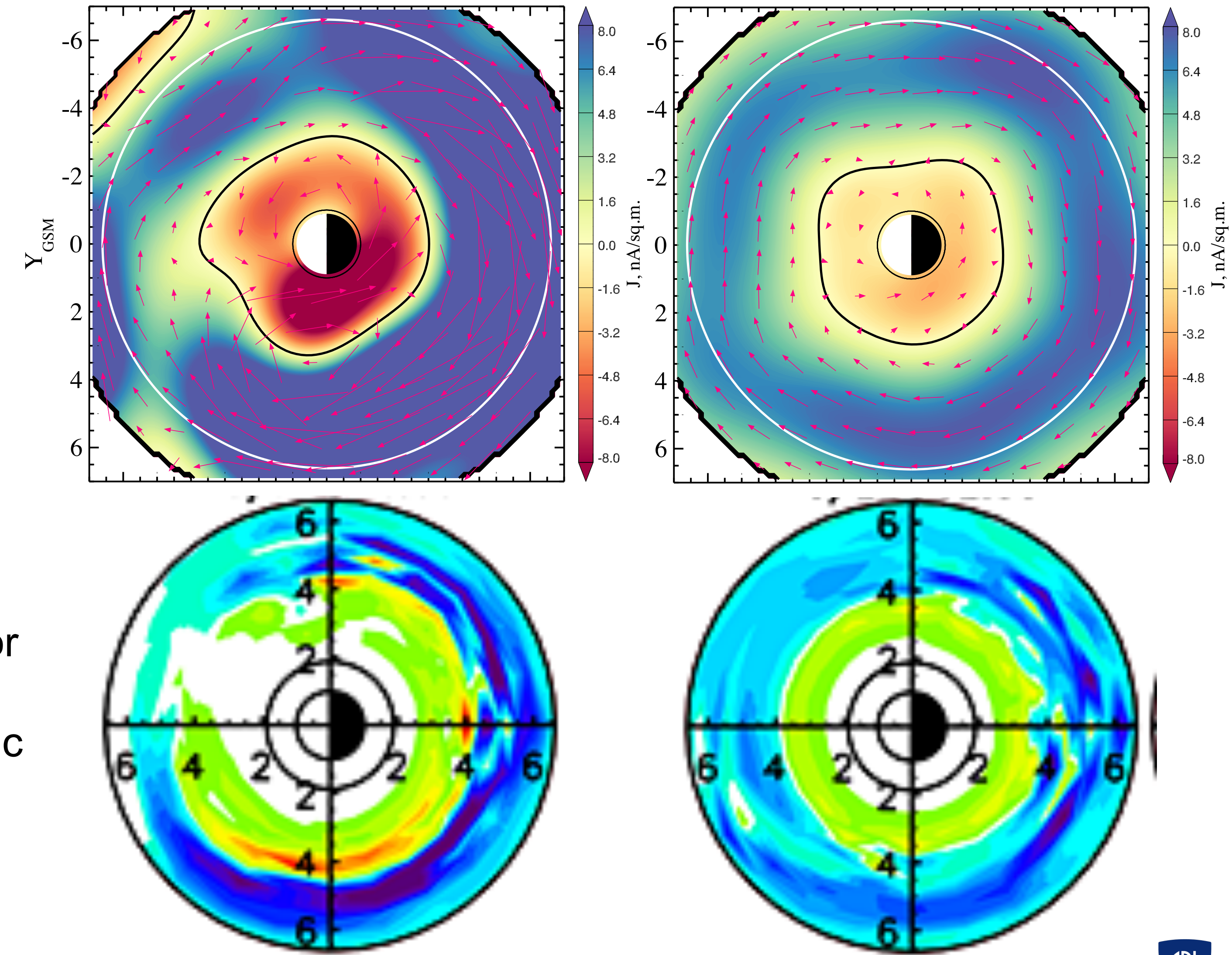
Comparison with HEIDI simulations

Near Dst* minimum

Recovery

Empirical Magnetic Field Model

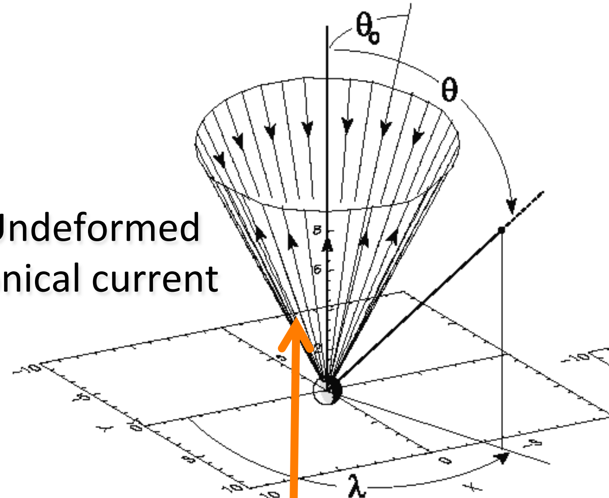
Hot Electron and Ion Drift Integrator with Self-Consistent electric field [*Liemohn et al.*, 2013]



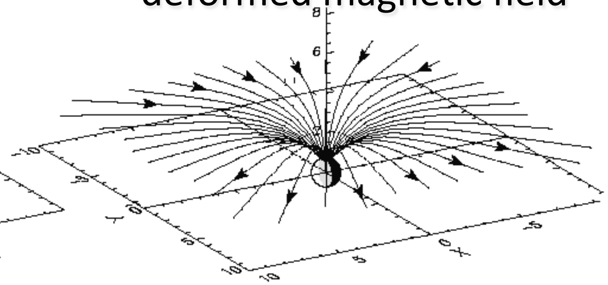
TS07D: Other current Systems

Field Aligned Current Module [Tsyganenko, 2002]

Undeformed conical current

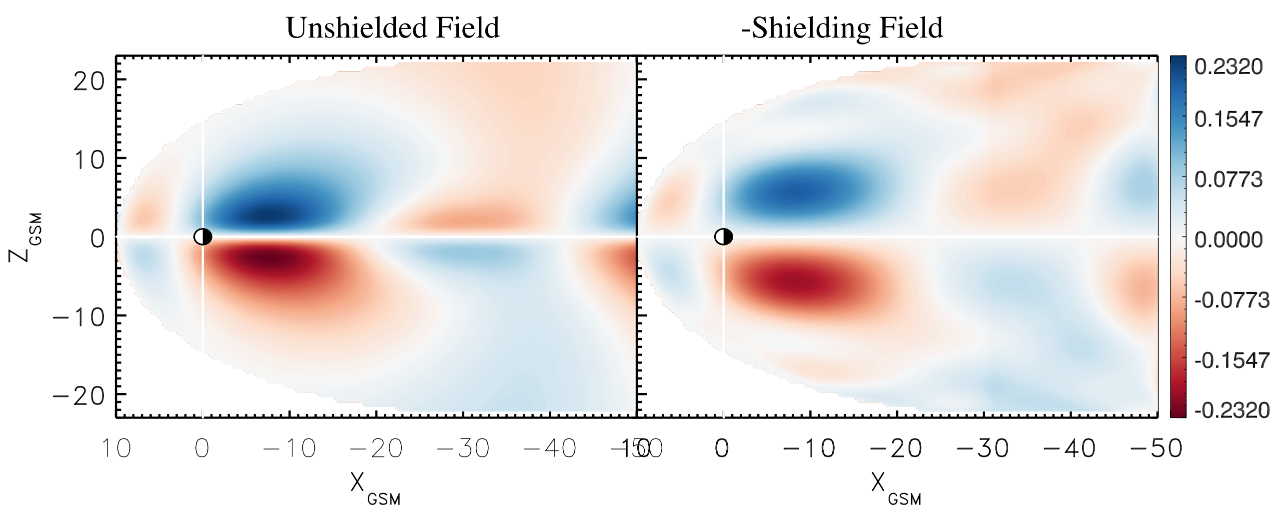


Currents corresponding to deformed magnetic field



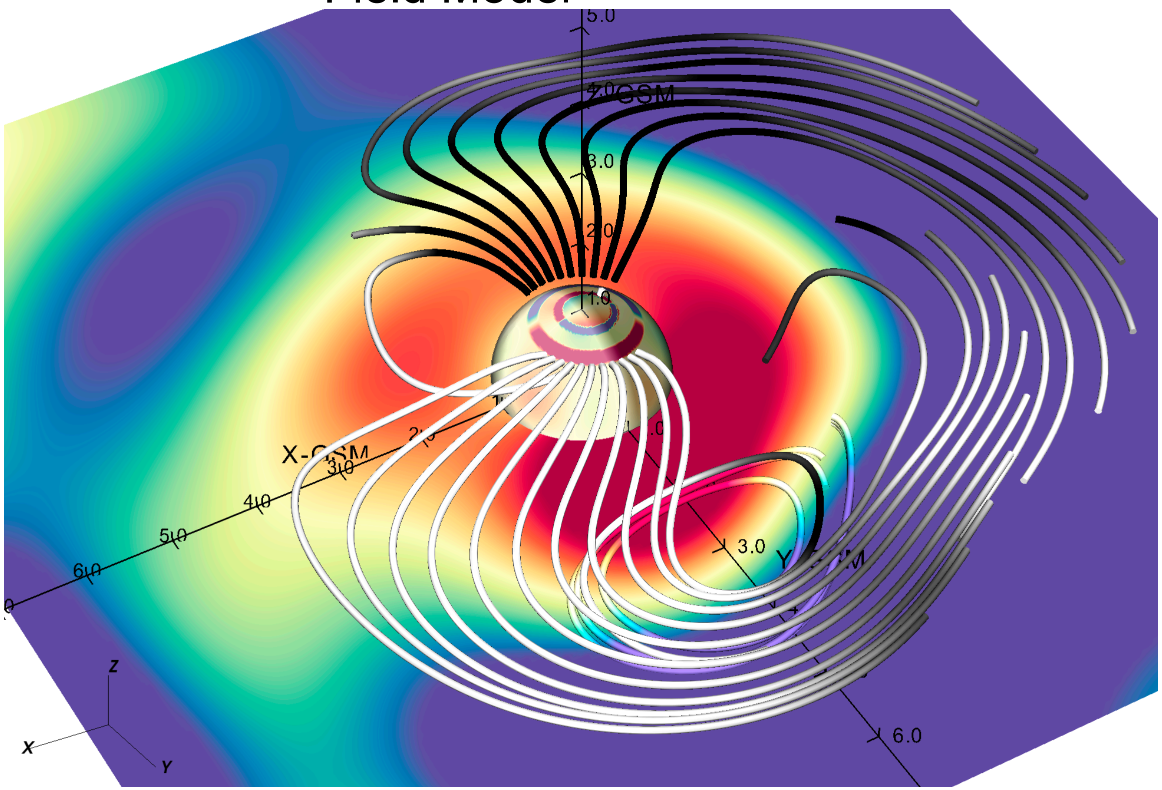
$$\mathbf{B}_E = \mathbf{B}_{CF} + \mathbf{B}_T + \mathbf{B}_{SRC} + \mathbf{B}_{PRC} + \mathbf{B}_{FAC} + \mathbf{B}_{INT}$$

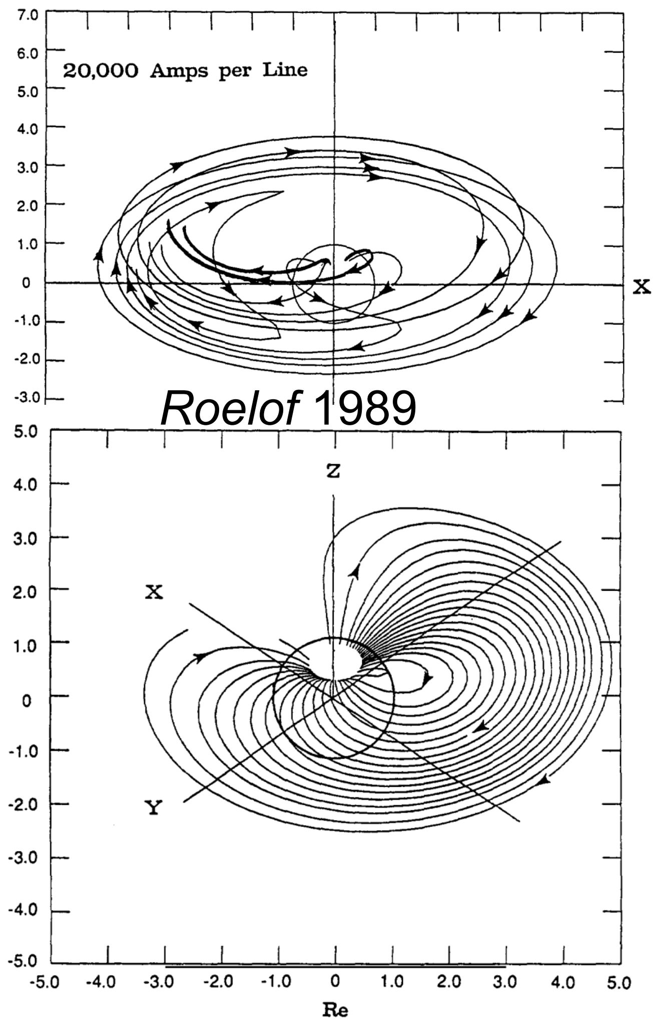
Shielding Fields:



Comparison with ENA images

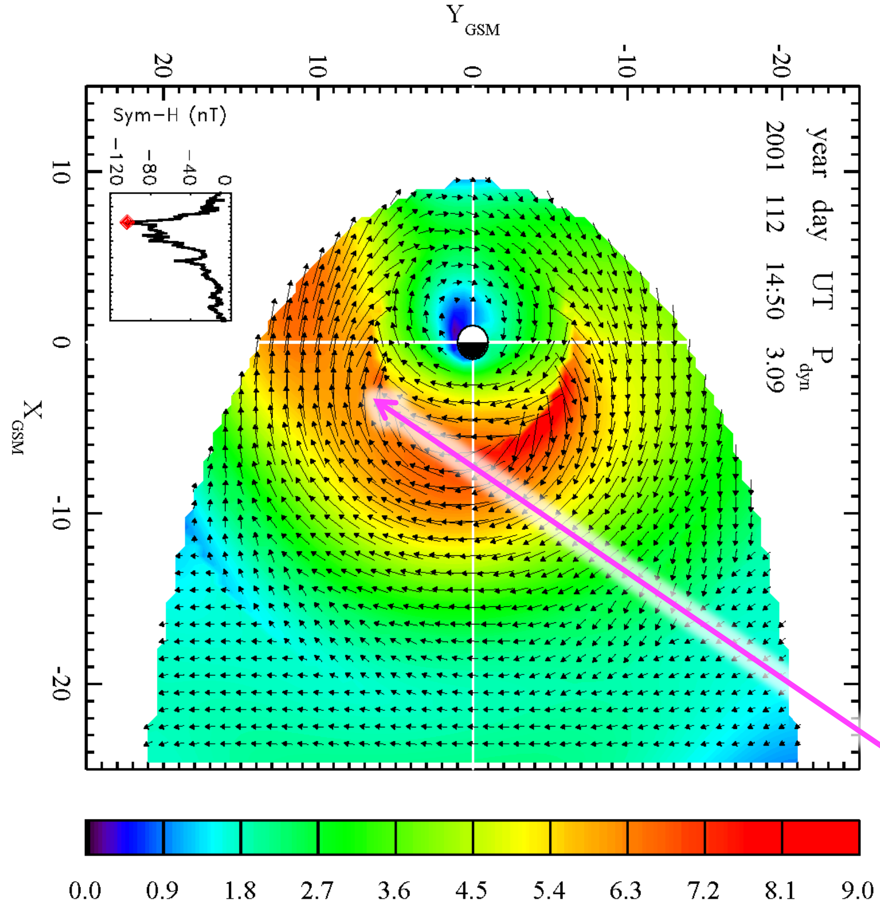
Empirical Magnetic Field Model





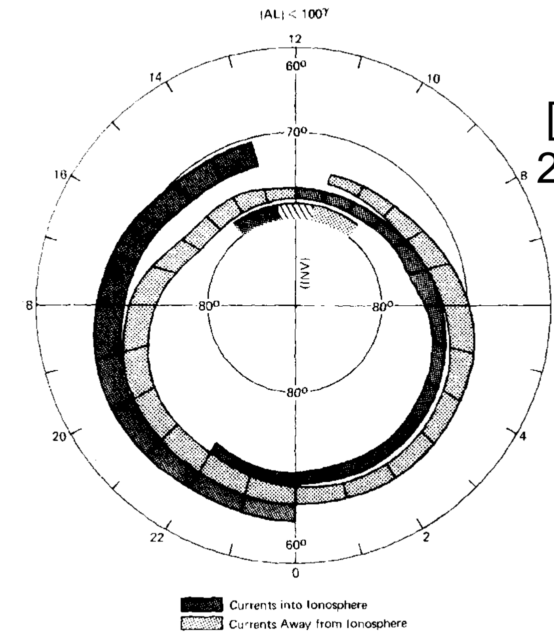
Roelof 1989

TS07D and TRIAD Results

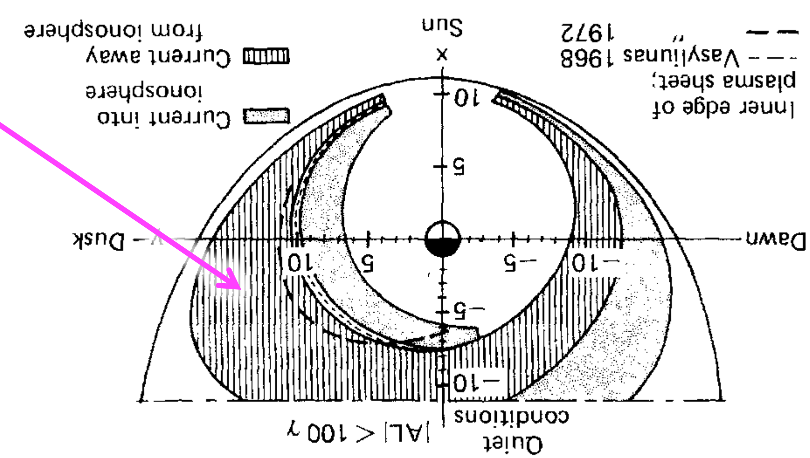


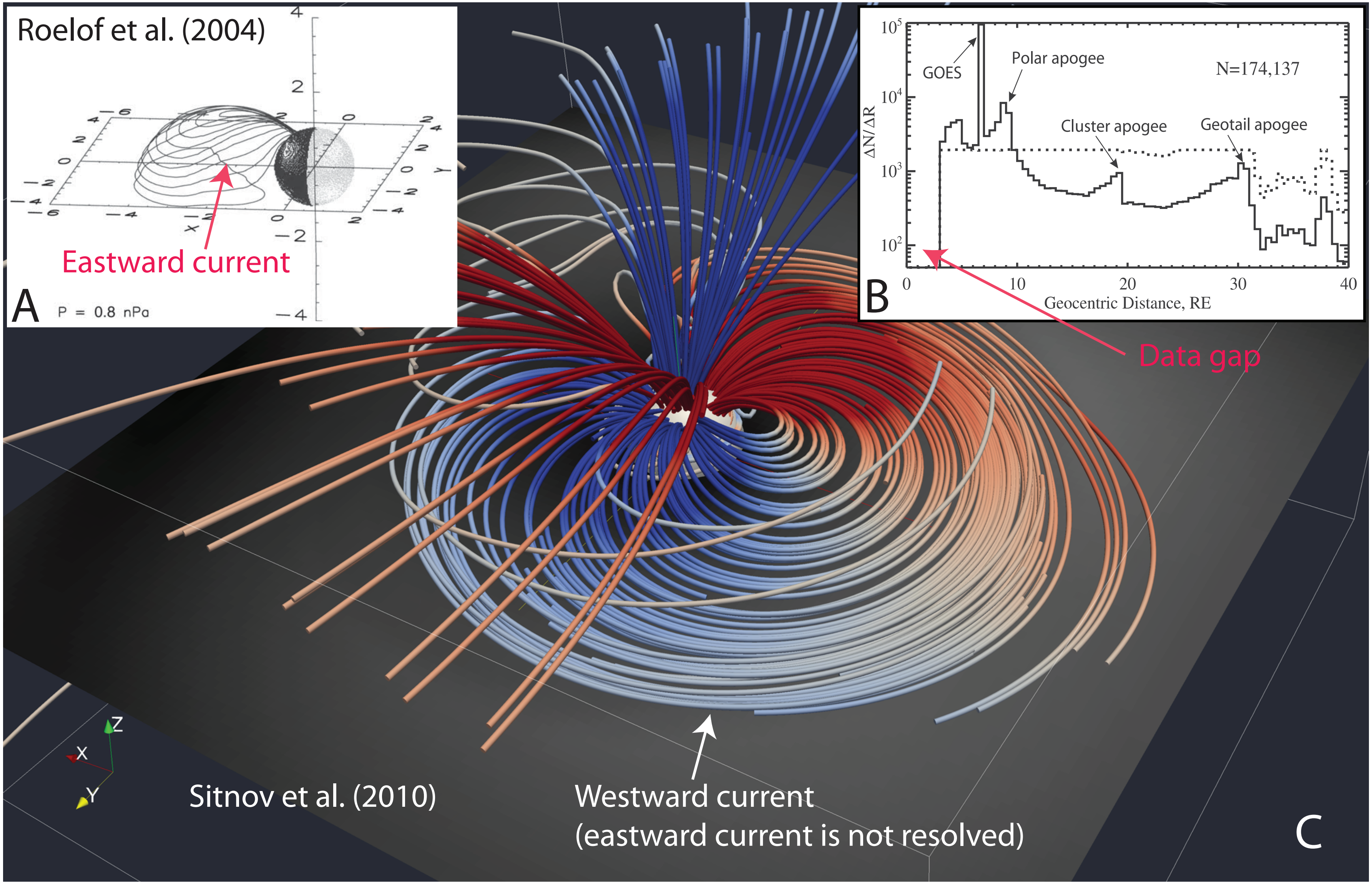
Hook-shaped current

Flow-out effect: Takahashi et al. [1990], Ebihara and Ejiri [1998], Liemohn et al. [1999]



Potemra [ASS, 58, 207,1978]

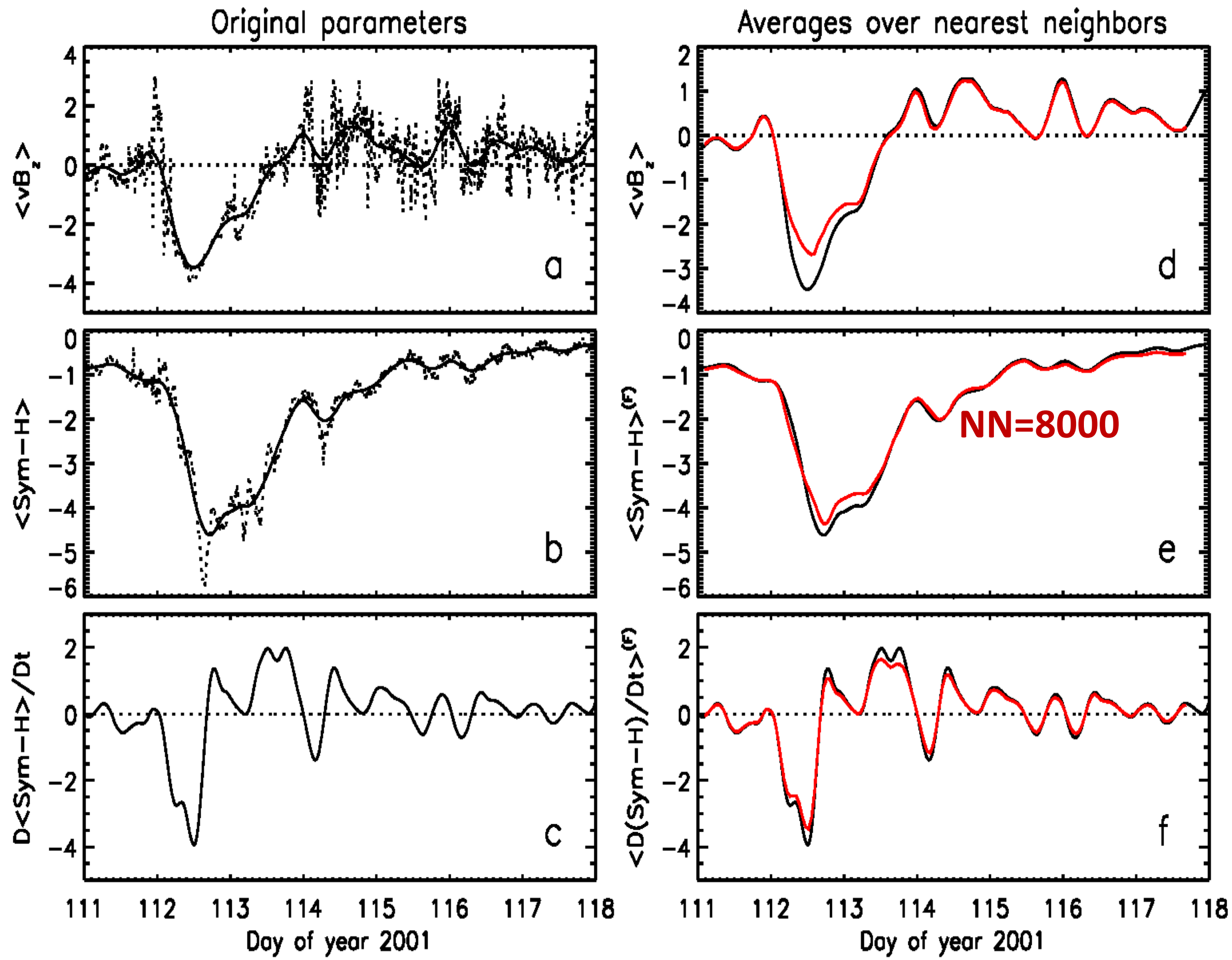




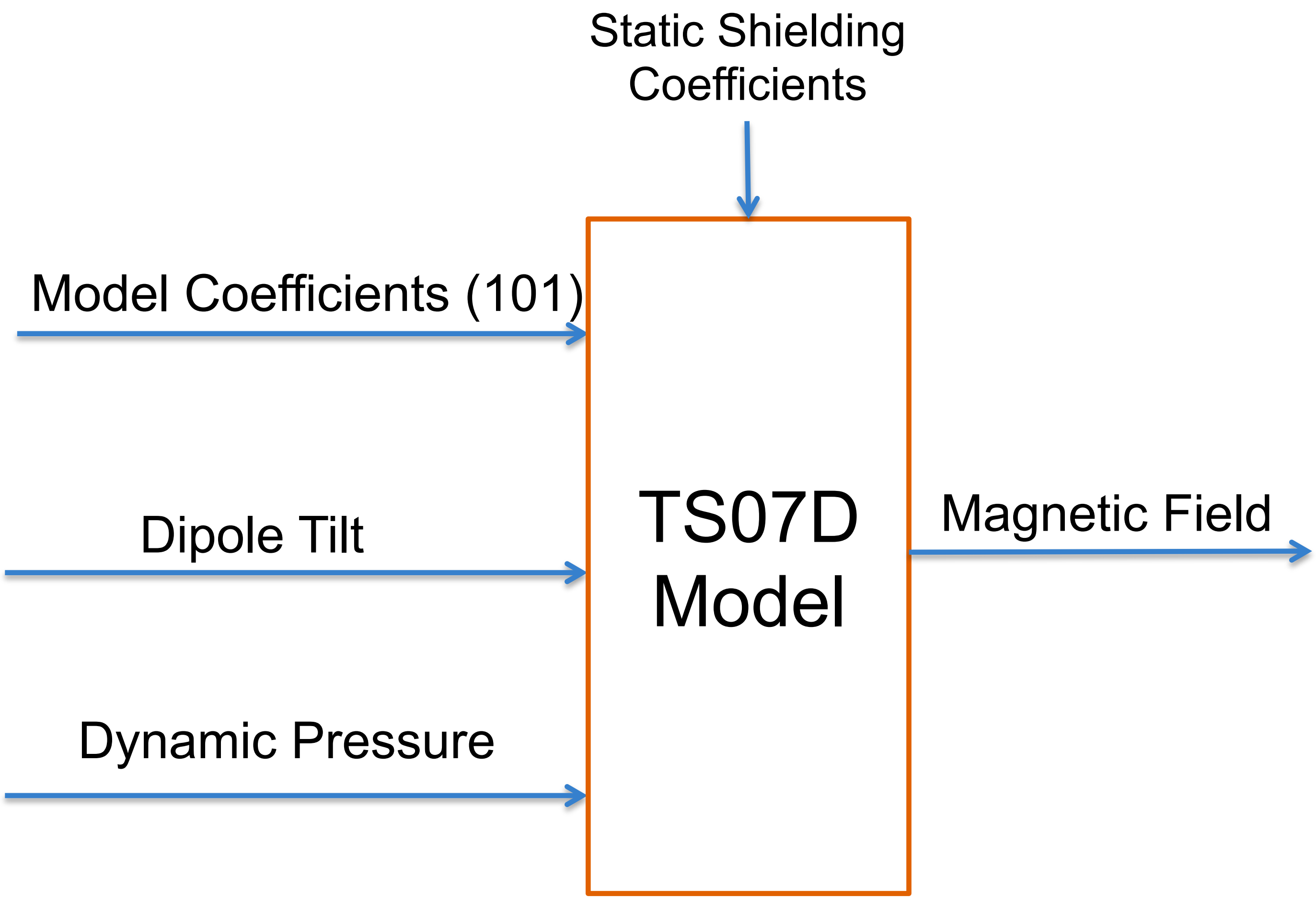
Roelof et al. (2004)
Eastward current
A
P = 0.8 nPa
B
GOES
Polar apogee
N=174,137
Cluster apogee
Geotail apogee
ΔN/ΔR
Geocentric Distance, RE
Data gap
Z
X
Y
Sitnov et al. (2010)
Westward current
(eastward current is not resolved)
C

TS07D: Dynamical binning using Nearest Neighbors

- NN parameters are based BMR formulism, relating vBz, Dst, and d/dt(Dst) to global state of the magnetosphere during storms [*Burton et al.* 1975]
- Selects other magnetometer data that is most similar to epoch we are modeling
- Balance between statistical approach and event oriented models



Using TS07D: Dynamic Inputs



Accessing Coefficients

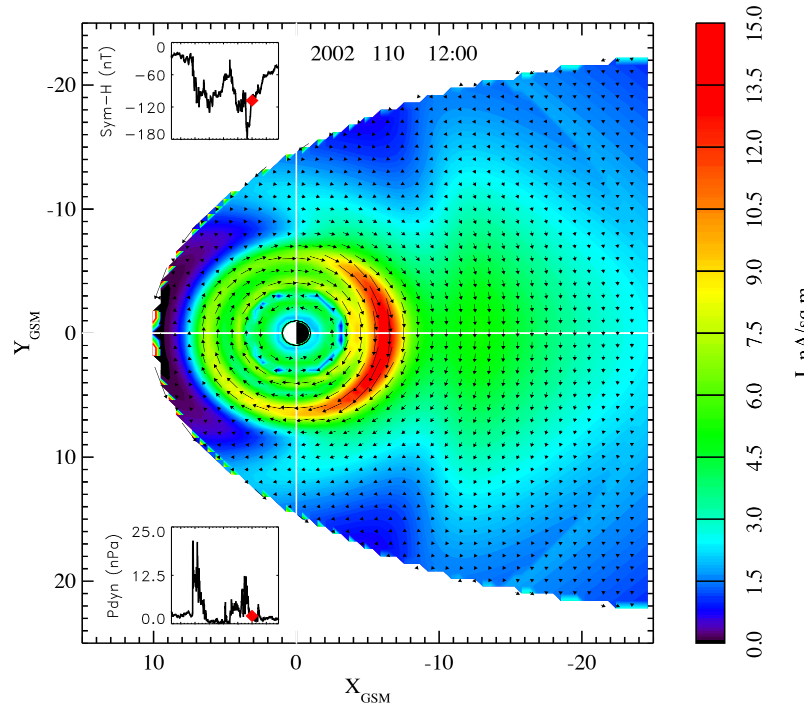
- **Hourly coefficients files have been pre-computed for August 15, 2012 – December 31, 2013**
- **Interpolated files have been created for every 5-min.**
- **These are also on the Science Gateway**
- **Files will continue to be updated as new OMNI files are released**
- **Coefficient Files have been augmented to include Dynamic pressure and dipole tilt**

```
  15.9402
 -14.7588
 -15.7975
  1.26810
 0.230058
 -1.17692
 0.137130
  2.72933
  10.7471
  15.0955
  1.08324
  1.67852
 0.119010E-01
     Q=      10.6383
B_rms=      25.6734
 Pdyn=         0.580000
 tilt=       -0.0131799
```

Classical Tsyganenko models

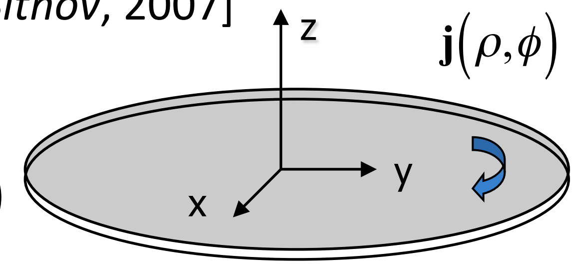
- Current systems are rigid modules structured from a priori assumptions about the morphology
- Modules have a limited number of parameters that determine spatial scale and intensity
- These parameters are functions of solar wind inputs (driving functions)
- Models are ‘climatological’, i.e. their temporal dependence is dependent on predetermined driving functions

TS05



TS07D: Equatorial Magnetic Field Description

Basic idea: Magnetic field of an current disc [*Tsyganenko and Sitnov*, 2007]



Ampere's Law: $$\nabla \times \mathbf{B} = \mu_0 \left[j_\rho(\rho,\phi)\hat{\mathbf{e}}_\rho + j_\phi(\rho,\phi)\hat{\mathbf{e}}_\phi \right]\delta(z)$$

When z ≠ 0: $$\nabla \times \mathbf{B} = 0 \rightarrow \mathbf{B} = -\nabla\gamma \rightarrow \nabla^2\gamma = 0$$

Solution of Laplace's Eq.: $$\gamma = \sum_{n=0}^{N}\sum_{m=1}^{M} C_{mn} J_m(k_n\rho) \left\{ \begin{array}{c} \cos(m\phi) \\ \sin(m\phi) \end{array} \right\} \exp(-k_n|z|)$$

$$k_n = n/\rho_0$$

$$\zeta = \sqrt{z^2 + D^2}$$

Magnetic Vector Potential:

$$\mathbf{A} = \sum_{n=1}^{N} a_{0n} J_1(k_n\rho)\exp(-k_n\zeta)\hat{\mathbf{e}}_\phi + \sum_{n=1}^{N}\sum_{m=1}^{M} a_{mn}\frac{-k_n\rho}{m}\left[J_m(k_n\rho)\hat{\mathbf{e}}_\rho + \frac{z}{\zeta}J'_m(k_n\rho)\hat{\mathbf{e}}_\phi \right] \left\{ \begin{array}{c} \cos(m\phi) \\ \sin(m\phi) \end{array} \right\} \exp(-k_n|z|)$$

TS07D: Equatorial Magnetic Field Description

$$\mathbf{B}_E = \underbrace{\mathbf{B}_{CF} + \mathbf{B}_T + \mathbf{B}_{SRC} + \mathbf{B}_{PRC}}_{\mathbf{B} = \nabla \times \mathbf{A}} + \mathbf{B}_{FAC} + \mathbf{B}_{INT}$$

Basis Function Expansion:

$$\boxed{\mathbf{B}_{Eq}\left(\mathrm{P_d}\right) = \sum_{n=1}^{N} t_n^{(s)} \mathbf{B}_{Tn}^{(s)} + \sum_{m=1}^{M}\sum_{n=1}^{N} t_{mn}^{(o)} \mathbf{B}_{Tmn}^{(o)} + \sum_{m=1}^{M}\sum_{n=1}^{N} t_{mn}^{(e)} \mathbf{B}_{Tmn}^{(e)}}$$

Add dynamic pressure dependence:

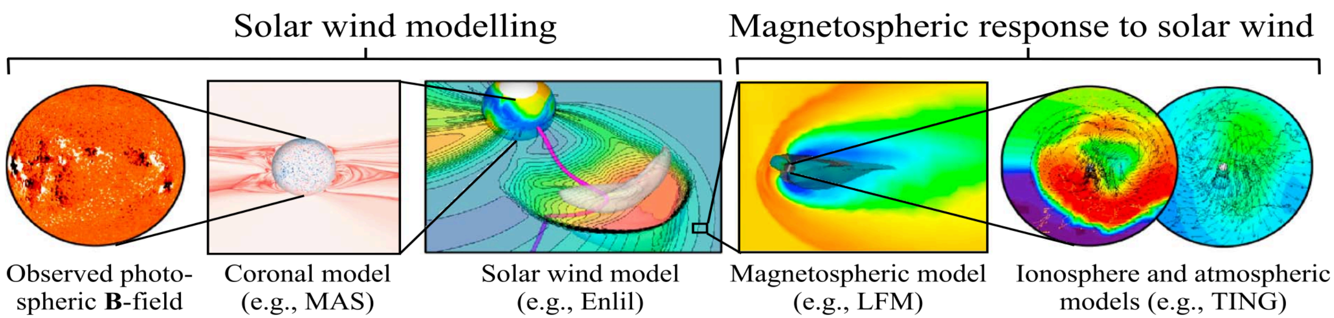
$$\mathrm{t}\left(\mathrm{P_d}\right) = t^{(0)} + t^{(1)}\sqrt{P_d}$$

Add dipole tilt angle (Ψ) dependence:

$$\mathbf{B}'_{Eq}\left(\mathrm{P_d}, \Psi\right) = \hat{\mathbf{T}}(\Psi)\mathbf{B}^{*}_{Eq}(\mathrm{P_d})$$

this deforms and warps the current sheet

Magnetosphere's Role in Space Weather

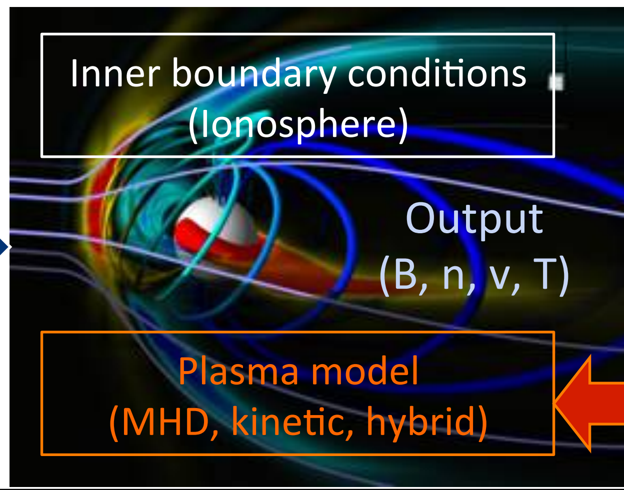


Owens et al. [2014]

Space Weather
Volume 12, Issue 6, pages 395-405, 9 JUN 2014 DOI: 10.1002/2014SW001064

First-principles approach

Solar wind input (B, n, v, T)



Maxwell and Vlasov equations

- **Magnetosphere can be thought as a black box integrator of a time series of various solar wind parameters**
- **First-principles (MHD and Kinetic) are often utilized**
- **Used to model the space weather events such as the geomagnetic storms and ring current, field aligned currents, substorms, and acceleration of charged particles into the inner-magnetosphere, etc…**

Limitations of First-principles models

- **MHD models**
  - Treats plasma as idealized fluid, thus neglects particle effects (particle drifts, wave-particle interactions)
  - Equation of state neglects plasma kinetics
  - MHD cannot fully describe the evolution of the storm-time ring current
- **Kinetic models**
  - Need boundary conditions
  - Are often limited to only geosynchronous orbit
  - Do not provide a global picture of the magnetosphere
- **Empirical models provide a 'Ground Truth' to complement these First-principles models**

April 17-21, 2002 storm:
TS07D 3D visualization